Processing, Characterization and Erosion Wear Behaviour of Coir Fiber Reinforced Epoxy Composites

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DEDICATED TO

MY BELOVED PARENTS, SON AND

HUSBAND

Declaration of Originality

I, Geetanjali Das, Roll Number 612ME306 hereby declare that this dissertation entitled "*Processing, Characterization and Erosion Wear Behaviour of Coir Fiber Reinforced Epoxy Composites*" represents my original work carried out as a postgraduate student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

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Abstract

Now-a-days, natural fibers have been receiving considerable attention as the substitute for synthetic fiber reinforcement such as glass in plastics. Among various fibers, coir is most widely used natural fiber due to its advantages like easy availability, low cost, low density, low production cost and satisfactory mechanical properties. The objective of the present research work is to study the physical, mechanical, water absorption and erosion wear behaviour of coir fiber reinforced epoxy composites filled with Al_2O_3 filler. Twenty different samples without filler and twenty samples with constant filler content of 10 wt% were prepared by varying the length of the fiber (3 mm, 6 mm, 9 mm, 12 mm and 15 mm) and content of fiber (5 wt%, 10 wt%, 15 wt% and 20 wt%) using hand lay-up technique. The density, hardness, tensile strength, tensile modulus, flexural strength, impact energy and percent of water absorption of the composites were analyzed. The erosion wear of these composites have been evaluated at different impingement angles (30°, 45°, 60°, 75° and 90°) and at different impact velocities (48 m/s, 70 m/s, 82 m/s and 109 m/s). The effect of fiber length and content on the properties of composites is also analyzed. A comparison has been made between composites with and without Al_2O_3 filler. It has been observed that composites filled with Al_2O_3 filler shows better mechanical and wear properties as compared to composites without filler. A multi-criteria decision making approach called TOPSIS is also used to select the best material from a set of alternatives. The morphology of eroded surfaces is examined by using scanning electron microscopy (SEM) and possible wear mechanisms are discussed.

Keywords: Al_2O_3 Particulate; Coir Fiber; Polymer Composites; Fiber Length; Fiber Content; Erosion Wear; Mechanical Properties.

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Chapter 1
Introduction

1.1 Background and Motivation

Engineering materials constitute the foundation of technology, whether the technology is applied to structural, thermal, electronic, electrochemical, biomedical, environmental or other applications. The history of human civilization is evolved from the Stone Age to the Bronze Age, the Iron Age, the Steel Age and to the Space Age [1]. Each age is marked by the advent of certain materials. The Iron Age brought tools and utensils, the Steel Age brought rails and industrial revolution, and the Space Age brought the even more advanced materials i.e. composite materials. The development of composite materials and their related design and manufacturing technologies is one of the most important advances in the history of materials. Basically, composites are materials consisting of two or more chemically distinct constituents, on a macro-scale, having a distinct interface separating them. One or more discontinuous phases are, therefore, embedded in a continuous phase to form a composite [2]. The properties of composite materials are superior in many respects, to those of the individual constituents. The discontinuous phase is usually harder and stronger than the continuous phase and is called the reinforcement, whereas, the continuous phase is termed as the matrix. The primary functions of the matrix are to transfer stresses between the reinforcing fibers/particles and to protect them from mechanical and/or environmental damage whereas the presence of fibers/particles in a composite improves its mechanical properties such as strength, stiffness etc. The objective is to take advantage of the superior properties of both materials without compromising on the weakness of either. The composite materials have advantages over other conventional materials due to their higher specific properties such as tensile, flexural and impact strengths, stiffness and fatigue properties, which enable the structural design to be more versatile. Due to their many advantages they are widely used in aerospace industry, mechanical engineering applications (internal combustion engines, thermal control, machine components), electronic packaging, automobile, and aircraft structures and mechanical components (brakes, drive shafts, tanks, flywheels, and pressure vessels), process industries equipment requiring resistance to high-temperature corrosion, dimensionally stable components, oxidation, and wear, offshore and onshore oil exploration and production, marine structures, sports, leisure equipment and biomedical devices [3, 4].

Generally, composite materials can be classified according to different criteria. According to the type of matrix materials, composite materials are classified into three categories, such as metal matrix composites (MMCs), ceramic matrix composites (CMCs) and polymer matrix composites (PMCs). Each type of composites is suitable for different applications. Among various types of composites, PMC is the most commonly used composites, due to its advantages such as simple manufacturing principle, low cost and high strength. When the matrix material is polymer, the composite is called polymer matrix composites. The properties of PMCs are mainly determined by three constitutive elements such as the types of reinforcements (particles/fibers), the type of polymer, and the interface between them. Polymers are divided into two categories such as thermoplastics and thermosets. Thermoplastic are in general, ductile and tougher than thermoset materials and are used for a variety of nonstructural applications without fillers and reinforcements. They are reversible and can be reshaped by application of heat and pressure. Thermoplastic molecules do not cross-link and therefore they are flexible and reformable [5]. Properties of thermoplastic polymer include high strength and toughness, chemical resistance, good durability, self-lubrication, transparency and water proofing. However, thermoplastics show poor creep resistance, especially at elevated temperatures, as compared to thermosets. Their lower stiffness and strength values require the use of fillers and reinforcements for structural applications. Some of the thermoplastic polymer materials are nylon, acrylonitrile butadiene styrene, polycarbonates, polyethylene, polyetheretherketone, acetal, polyvinyl chloride etc. Thermoplastic polymer are used to manufacture dashboard, toys, electrical products, bearings, gears, ropes, glass frames, hoses, sheet etc. Thermoset are materials that undergo a curing process through part fabrication and once cured cannot be re-melted or reformed. Thermoset materials are brittle in nature and offer greater dimensional stability, better rigidity, and higher chemical, electrical, and solvent resistance. The most common resin materials used in thermoset composites are epoxy, polyester, phenolics, vinyl ester, and polyimides. Applications in which these are used are electrical equipment, motor brush holders, printed circuit boards, circuit breakers, encapsulation material, kitchen utensils, handles, knobs, spectacle lenses etc. Among them epoxy is the most widely used matrix due to its advantages like good adhesion to other materials, good mechanical properties, good electrical insulating properties, good chemical and environmental resistance etc.

According to the reinforcement, the polymer composites are classified into two categories such as particulate reinforced polymer composites and fiber reinforced polymer (FRP) composites. The particle reinforced composites mainly consisting of reinforcing material that is in the form particle. The shape of particles may be cubic, spherical, a platelet, tetragonal, regular and irregular geometry. The arrangement of the particles in the composites either randomly or preferred orientation. Usually the particles are used in reduce friction, improve machinability, electrical and thermal conductivities, improve performance at elevated temperatures, increase wear and abrasion resistance, reduce shrinkage and increase surface hardness of the materials. Recently, FRP composites have been widely used in various applications such as aerospace, automotive, marine etc. due to their advantages such as high specific stiffness and strength [6]. These materials also provide high durability, light weight and design flexibility, which make them attractive materials in these applications. FRP composites consisting of reinforcing fibers embedded in a rigid polymer matrix. Properties of FRP composites are determined by many factors such as properties of the fibers, fiber length, concentration of the fibers, orientation of the fibers, fiber-matrix interface strength, properties of the matrix etc. Therefore, in order to obtain the favoured material properties for a particular application, it is important to know how the material performance changes with these factors.

With the growing global energy crisis and ecological risks, natural fiber reinforced polymer composites have attracted more research interests due to their potential of serving as alternative for synthetic fiber reinforced composites. Compared to synthetic fiber based composites, the natural fiber composites are having the advantages such as low cost, easy availability, renewability, light weight and high specific strength, and stiffness [7]. A great deal of work has been done on the polymer composites reinforced with different types of natural fibers such as jute, banana, coir, wood fiber palm, flax and kenaf etc. [8]. Among them, coir fibers are extensively used now-a-days in many industrial applications. Coir is a natural fiber extracted from the husk of coconut fruit. It is a fiber which is highly available in India the second highest in the world after Philippines [9]. Coir fiber has many advantages like low cost, low density, versatile, high stiffness, renewability, waterproof, biodegradability and high degree of flexibility during processing [10]. Compare to other natural fibers, the coir fiber has remarkable interest in many industries due to its high hardness and hard-wearing quality, not toxic, good acoustic resistance, resistant to microbial and fungi degradation, and not easily combustible. The coir fibers are also more resistant to moisture than other natural fibers and withstand heat and salt water [11]. Coir consists of cellulosic fibers with hemi-cellulose and lignin as the bonding materials for the fibers. The fiber becomes stiffer, tougher and more long-lasting compared to other natural fibers because the lignin content in coir fiber is quite high. Coir fiber is widely used for preparing mats, ropes, mattresses, yarns, sacking, brushes, caulking boats, floor tiles and insulation panels etc. The coir fiber nets are used to prevent soil destruction during heavy rains and cyclones. It is reported that in the world about 55 billion of coconuts are produced yearly and only 15% of the coir fibers are actually recovered for use, leaving most coir abandoned. Coir based composites enjoying broader applications in automobiles and railway coaches & buses for public transport system. Coconut coir is a waste of natural resources and a cause of environment pollution. Hence, research and development efforts have been going on to find out the new areas for coir, along with utilization of coir as reinforcement in polymer composites. As reinforcement in polymer composites, coir fibers have demonstrated a great deal of potential. However, tribo-characterization of these coir composites is still in the formative stages [12]. In view of this, the present research work is undertaken to study the reinforcement potential of coir fibers in polymer composites.

Major constituents in FRP composites are the reinforcing fibers and a matrix. In addition, particulate fillers can also be used mainly to reduce the cost and improve the dimensional stability. The incorporation of these filler into polymer has been proved to be an alternative for the enhancement of the performance of the resultant composites and so has lately been a subject of considerable interest. So, even if a judicious selection of reinforcement and the matrix phase can lead to a composite with a combination of strength and modulus comparable to or even better than those of conventional metallic materials [13], the properties can further be modified by adding a solid filler phase to the matrix during the composite preparation. Such multi-component composites consisting of a matrix phase reinforced with a fiber and filler are termed as hybrid composites. The term ‘filler’ is very broad and encompasses a very wide range of materials. Aluminium oxide (Al_2O_3) is a ceramic material that has the potential to be used as filler in various polymer matrices. Generally, Al_2O_3 referred to as ‘alumina’ which belongs to engineering ceramics family is the most cost effective and extensively used material. Al_2O_3 is hard, wear-resistant, has accomplished dielectric properties, resistance to strong acid and alkali attack at elevated temperatures, high strength and stiffness. With a superb combination of properties and a sensible value, it is no wonder that fine grain technical grade Al_2O_3 has a very wide range of applications.

Polymers and polymer composites are being used increasingly often as engineering materials for technical applications in which tribological properties are of considerable importance. The word tribology was first reported in a landmark report by Jost in 1966. The word is derived from the Greek word *tribos* meaning rubbing [14]. Since its definition, tribology has been widely recognized as a general concept embracing all aspects of the transmission and dissipation of energy and materials in mechanical equipment including the various aspects of friction, wear, lubrication and related fields of science and technology [15]. The enormous cost of tribological deficiencies to any national economy is mostly caused by the large amount of energy and material losses occurring simultaneously on virtually every mechanical device in operation. Wear is the surface damage or removal of material from one or both of two solid surfaces in a sliding, rolling, or impact motion relative to one another. Wear is not catastrophic but, in most cases, it certainly reduces operating efficiency. It results in dimensional changes of the components or damage to the surface. This causes an associated problem of vibrations and/or misalignments. The propagation of cracks formed at or near the stressed surface may in extreme cases lead to fracture of the component. Components lose their applicability as a result of change in dimensions due to surface damage or wear. In engineering material science, wear are classified into five distinct types such as adhesive, abrasive, erosive, corrosive and surface fatigue. Solid particle erosion, a typical erosive wear mode, is the loss of material that results from repeated impact of small, solid particles. Polymer composites are finding applications that subjected to solid particle erosion. Examples of such applications are in petroleum refining pipe line carrying sand slurries, high speed vehicles and aircraft operating in desert environments, pump impeller blades, aircraft engine blades, water turbines, helicopter rotor blades etc. [16-18]. Hence, erosion resistance of polymer composites has become an important material property, particularly in selection of alternative materials and therefore the study of solid particle erosion characteristics of the polymeric composites has become highly relevant. Also a full understanding of the effects of all system variables on the wear behaviour is essential in order to undertake appropriate steps in the choice of materials and in the design of machine or structural component to reduce/control wear.

Material selection is one of the most challenging issues for designing and developing any structural component. The success of any component depends on the better performance and low cost of material used. Thus, it becomes a real challenge for the designers to optimally select material from the vast range of available materials that satisfy the complex design problems. Now-a-days, multi-criteria decision making (MCDM) approach is used as an effective tool for material selection of complex design problems [19]. The MCDM process involves creating alternatives, forming the required criteria and assessing the alternative materials using a set of criteria weights. The outcome of these steps is a ranked list of alternative solutions [20]. Various MCDM techniques like simple additive weighted (SAW) method, weighted product method (WPM), technique for order preference by similarity to ideal solution (TOPSIS), Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) method, analytical hierarchy process (AHP), graph theory and matrix representation approach (GTMA), etc are used depending upon the complexity of the situation in engineering decision making problems [21-23]. Among various MCDM approaches, TOPSIS method offers a number of benefits [24]. The TOPSIS is one of the well-known MCDM method and was developed by Hwang & Yoon in the year 1981. The principle behind the TOPSIS is simple. Generally, ideal and negative-ideal solutions are formed. The ideal solution is formed as a composite of the best performance value exhibited by any alternative for each attribute and the negative-ideal solution is the composite of the worst performance values. The chosen alternative should be as close to the ideal solution as possible and as far from the negative-ideal solution as possible [25]. TOPSIS has been applied to a number of applications; however use of this technique for selection of materials is limited in the literature. Therefore, an attempt has been made to obtain the best alternative from the set of composite materials under the present study using TOPSIS.

To this end, the present research work is undertaken to study the physical, mechanical, water absorption and erosion wear behaviour of coir fiber reinforced polymer composites with Al_2O_3 filler. Attempts have been made to explore the potential use of coir fiber as reinforcement in polymer composites. The specific objectives of this work are clearly outlined in the next chapter.

1.2 Thesis Outline

The remainder of this thesis is organized as follows:

Chapter 2. Includes a literature review to provide a basic knowledge of the main subjects presented in this thesis. It presents the research works carried out by various investigators specifically on erosion wear behaviour of polymer composites.

Chapter 3. Provides detail information of the raw materials used, fabrication technique, test procedures, and characterization of the composites under study and also a description of TOPSIS method.

Chapter 4. Presents the test results of physical, mechanical and water absorption behaviour of composites.

Chapter 5. Presents the test results of erosion wear behaviour of the composites under study.

Chapter 6. Presents the ranking of composites using TOPSIS method.

Chapter 7. Provides summary of the findings of this research work, outlines specific conclusions drawn from the experimental investigation and suggests ideas and directions for future research.

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Chapter 2
Literature Review

The purpose of this literature review is to provide background information on the issues to be considered in this thesis and to emphasize the relevance of the present study. This treatise embraces various aspects of polymer composites with a special reference to their erosion wear characteristics. This chapter includes reviews of available research reports:

- On natural fiber and natural reinforced composites
- On mechanical properties of natural fiber composites
- On coir and coir fiber reinforced composites
- On use of fillers in polymer composites
- On erosion of polymer composites
- On TOPSIS

At the end of the chapter a summary of the literature survey and the knowledge gap in the earlier investigations are presented. Subsequently the objectives of the present research work are also outlined.

2.1 On Natural Fiber and Natural Fiber Reinforced Composites

Fibers in polymer composites can be either synthetic/man-made fibers or natural fibers. Some commonly used synthetic fibers for composites are glass, aramid and carbon etc. If the fibers are derived from natural resources like plants or some other living species, they are called natural fibers. It is also known that natural fibers are non-uniform with irregular cross sections, which make their structures quite unique and much different from man-made fibers. Advantages of natural fibers over synthetic fibers include low density, high availability, low cost, recyclability and biodegradability [26]. The natural fiber based composites are classified into different categories according to their source of origin such as vegetable or plant fibers, animal or protein fibers and mineral fibers. Figure 2.1 shows the classification of the natural fibers [27]. The properties of some of these fibers are presented in Table 2.1 [28]. From the table it can be seen that the tensile strength of glass fiber is substantially higher than that of natural fibers even though the modulus is of the same order. However, when the specific modulus of natural fibers (modulus/specific gravity) is considered, the natural fibers show values that are comparable to or better than those of glass fibers. These higher specific

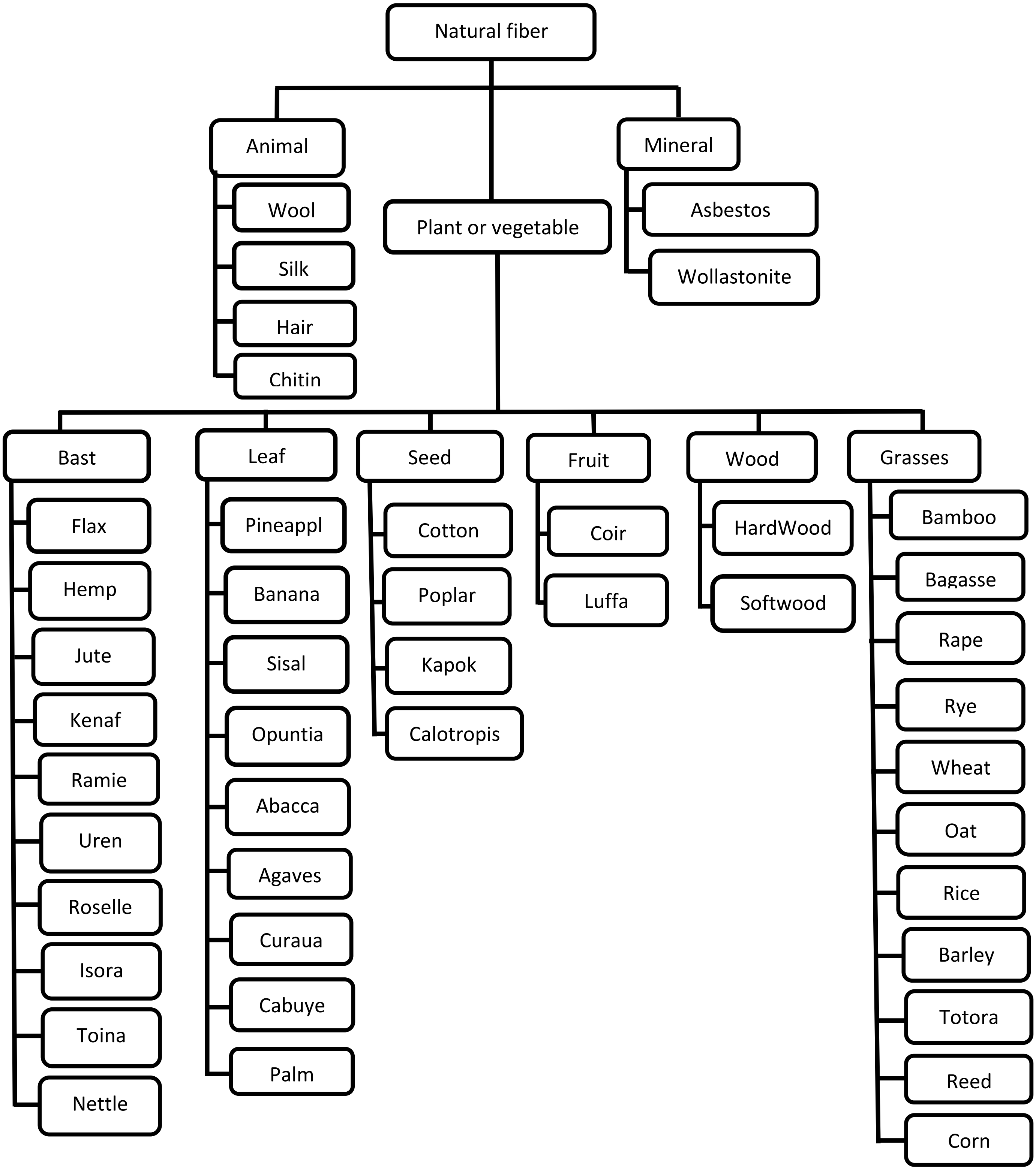

Figure 2.1: Classification of natural fibers [27]

properties are the major advantages of using natural fiber composites for applications where in the desired properties also include weight reduction.

Table 2.1: Properties of Natural Fibers [28]

Fiber	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Density (g/cm^3)
Abaca	400	12	3-10	1.5
Alfa	350	22	5.8	0.89
Bagasse	290	17	-	1.25
Bamboo	140-230	11-17	-	0.6-1.1
Banana	500	12	5.9	1.35
Coir	175	4-6	30	1.2
Cotton	287-597	5.5-12.6	7-8	1.5-1.6
Curaua	500-1,150	11.8	3.7-4.3	1.4
Date palm	97-196	2.5-5.4	2-4.5	1-1.2
Flax	345-1,035	27.6	2.7-3.2	1.5
Hemp	690	70	1.6	1.48
Henequen	500 ± 70	13.2 ± 3.1	4.8 ± 1.1	1.2
Isora	500-600	-	5-6	1.2-1.3
Jute	393-773	26.5	1.5-1.8	1.3
Kenaf	930	53	1.6	-
Nettle	650	38	1.7	-
Oil palm	248	3.2	25	0.7-1.55
Piassava	134-143	1.07-4.59	21.9-7.8	1.4
Pineapple	400-627	1.44	14.5	0.8-1.6
Ramie	560	24.5	2.5	1.5
Sisal	511-635	9.4-22	2.0-2.5	1.5
E-Glass	3400	72	-	2.5

The natural fibers structure is very interesting because it consists of multi-layered structures as shown in Figure 2.2 [29]. The primary layer which forms cell growth and it surrounds the secondary layers. The position of middle layer is thick among secondary walls and that determines mechanical property of fiber. The main content of natural fiber is cellulose micro fibrils which are bonded by amorphous materials called hemicellulose. The angle between micro fibrils orientation in the structure and the axis of main fiber body is called microfibrillar angle. The microfibrillar angle is different for different natural fibers and that determines the mechanical strength of fibers. The main thing is that the natural fibers itself act as a composite material where amorphous materials like pectin, hemicellulose and wax acts as a matrix which bonds the microfibrillar cellulose. Generally, the hemicellulose molecules are creating hydrogen bond to microfibrillar cellulose and act as a binding material. Lignin acts as a coupling agent which helps to increase the stiffness of the cellulose/hemicellulose composite. The physical and mechanical properties of natural fibers are greatly influenced by their chemical compositions. The chemical composition of natural fibers may differ with the growing condition and test methods even for the same kind of fiber. Mechanical properties of natural fibers are much lower when compared to those of the most widely used competing reinforcing glass fibers [30]. However, because of their low density, the specific properties (property-to-density ratio), strength, and stiffness of plant fibers are comparable to the values of glass fibers [31]. Knowledge of different types of natural fibers, their structure, properties, and chemical composition is necessary for development of natural fiber reinforced polymer composites for use in a specific application.

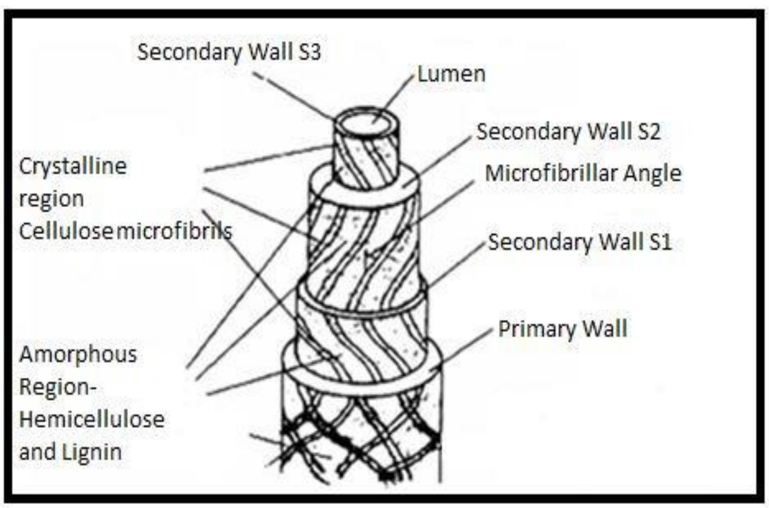

Figure 2.2: Structure of natural fiber [29]

In recent years, natural fiber reinforced polymer composites have attracted increasing research interests owing to their potential as an alternative for composites reinforced with synthetic fibers like glass or carbon. A number of investigations have been made on the use of various natural fibers such as kenaf, hemp, flax, bamboo and jute as reinforcement for polymer composites. Saheb and Jog [4] have also presented a very elaborate and extensive review on natural fiber reinforced composites with special reference to the type of fibers, matrix polymers, treatment of fibers and fiber-matrix interface. Kozlowskiy and Wladyka-Przybyl [27] done a review on the use of natural fibers for polymer composites and study their fire performance. Li et al. [32], done a review on the use of different chemical modifications on natural fibers for use in natural fiber reinforced polymer composites. John and Anandjiwala [28] have done a critical review of the literature on the various aspects of natural fibers and natural fiber reinforced composites with a particular reference to chemical modifications. Taj et al. [33] examined the different types of fibers available and the current status of research on the use of these fibers for polymer composites. They also reported that the use of natural fibers within composite applications is being pursued extensively throughout the world. The diverse range of products now being produced, utilizing natural fibers and bio-based resins derived from soybeans, is giving life to a new generation of bio-based composites for a number of applications. These include not only automotive vehicles but also hurricane-resistant housing and structures. The construction sector and the leisure industry are some of the other areas where these novel materials are finding a market. Natural fiber reinforced composites can also be applied in the automobile and packaging industries to cut down on material cost.

2.2 On Mechanical Properties of Natural Fiber Composites

Generally, the mechanical properties of natural fiber composites are strongly influenced by many factors such as volume fraction of the fibers, fiber-matrix adhesion, fiber aspect ratio, fiber orientation, stress transfer at the interface etc. [34]. Therefore, both the matrix and fiber properties are important in improving mechanical properties of the composites. A great deal of work has already been done on the effect of various factors on mechanical behaviour of natural fiber reinforced polymer composites. Luo and Netravali [35] studied the tensile and flexural properties of green composites with different pineapple fiber content and compared them with the virgin resin. Srivastav et al. [36] have studied the effect of different loading rate on mechanical behaviour of jute/glass reinforced epoxy hybrid composites. Hu et al. [37] studied the moisture absorption, tensile strength behaviour of short jute fiber/polylactide composite in hygrothermal environment. It was reported that for uncoated sample, the moisture absorption process includes three distinct stages such as quick moisture absorption stage, a slow steady increasing of moisture uptake stage and a very rapid moisture absorption stage. The whole moisture absorption process until the complete relaxation of the samples does not show moisture saturation. Schneider and Karmaker [38] developed composites using jute and kenaf fiber in polypropylene resin and reported that jute fiber provides better mechanical properties than kenaf fiber. Gowda et al. [39] evaluated the mechanical properties of jute fabric-reinforced polyester composites and found that they have better strengths than those of wood based composites. Basiji et al. [40] studied the effect of fiber length and fiber loading on the mechanical properties of wood-plastic (polypropylene) composites. Cazaurang et al. [41] carried out a systematic study on the properties of henequen fiber and pointed out that these fibers have mechanical properties suitable for reinforcement in thermoplastic resins. Dynamic mechanical analysis of natural fibers like sisal, pineapple leaf fiber, oil palm empty fruit bunch fiber etc. in various matrices has been made by Joseph et al. [42] and George et al. [43]. Harish et al. [44] studied the mechanical behaviour such as tensile strength, flexural strength and impact strength of coir/epoxy composites. Sapuan et al. [45] carried out tensile and flexural tests on natural fiber reinforced musaceae/epoxy composites. Similarly, an investigation on pulp fiber reinforced thermoplastic composite exhibited that while the stiffness is increased by a factor of 5.2, the strength of the composite is increased by a factor of 2.3 relative to the virgin polymer [46]. Shibata et al. [47] have investigated the effect of the volume fraction and length of natural fibers like kenaf and bagasse on flexural properties of some biodegradable composites. Luo and Netravali [35] studied the mechanical and thermal properties of environment-friendly "green" composites made from pineapple leaf fibers and poly (hydroxybutyrate-covalerate) resin. Tensile and flexural properties of the "green" composites with different fiber contents were measured. Pavithran et al. [48] determined the fracture energies for sisal, pineapple, banana and coconut fiber reinforced polyester composites using Charpy impact tests. They found that, except for the coconut fiber, increasing fiber toughness was accompanied by increasing fracture energy of the composites. Bos et al. [49] studied the mechanical properties of flax/polypropylene compounds, manufactured both with a batch kneading and an extrusion process. The structural characteristics and mechanical properties of coir fiber/polyester composites were evaluated and the effect of the molding pressure on the flexural strength of the composites was studied [50]. In another study, Okubo et al. [51] reported that the tensile strength and modulus of polypropylene based composites using steam-exploded bamboo fibers are higher than the composites using mechanically extracted fibers by about 15% and 30% respectively. Chen et al. [52] tested the mechanical properties of bamboo fiber reinforced polypropylene and compared them with those of commercial wood pulp. Shin et al. [53-55] investigated the mechanical properties and fracture mechanisms of bamboo-epoxy composites under different loading conditions. They also compared the mechanical properties of various types of composites at different combination of fibers and resins. Chawla and Bastos [56] studied the effect of fiber volume fraction on Young’s modulus, maximum tensile strength and impact strength of untreated jute fibers in unsaturated polyester resin, made by a leaky mould technique. Tobias [57] examined the influence of fiber content and fiber length in banana fiber reinforced epoxy composites and noticed that the impact strength increased with higher fiber content and lower fiber length. Hepworth et al. [58] investigated the mechanical behaviour of unidirectional hemp fiber reinforced epoxy composites. Alamri et al. [59] studied the mechanical and water absorption behaviour of recycled cellulose fiber reinforced epoxy composites. It was observed that exposure to moisture for two weeks caused a reduction in flexural strength, flexural modulus and fracture toughness due to the degradation of bonding at the fiber-matrix interfaces. However, impact strength was found to increase slightly after water absorption. The effect of water absorption on mechanical properties was more pronounced at high fiber content than at the low fiber content. Santulli [60] studied the post-impact behaviour of plain-woven jute/polyester composites subjected to low velocity impact and found that the impact performance of these composites was poor. Amash and Zugenmaier [61] reported on the effectiveness of cellulose fiber in improving the stiffness and reducing the damping in polypropylene-cellulose composites. A number of reports are available on investigations carried out on various aspects of polymer composites reinforced with banana fibers [62-65].

2.3 On Coir and Coir Fiber Reinforced Composites

Coconut coir fiber is the seed hair or husk. Husk of coconut is easily available in large quantities as residue from coconut production in many areas. Coir is a lingo-cellulosic natural fiber. The coir fiber industry is the one of the important industry of some areas of the developing world because of the advantages like hard-wearing quality, durability etc. These have wide application in of floor furnishing materials, yarn, rope etc. However, these coconut coir uses consume only a small percentage of the potential total world production of coconut husk. Hence, research and development efforts have been going on to find out the new areas for coir, along with utilization of coir as reinforcement in polymer composites. Verma et al. [9] studied a detail review on the coir fiber reinforcement and application in polymer composites. Harish et al. [44] studied the mechanical behaviour such as tensile strength, flexural strength and impact strength of coir/epoxy composites. Ayrilmis et al. [66] studied on coir fiber reinforced polypropylene composite panel for automotive interior applications. This study showed that the coir fiber is a potential candidate in the manufacture of reinforced thermoplastic composites, especially for partial replacement of high-cost and heavier glass fibers. Monteiro et al. [50] studied the mechanical performance of coir fiber/polyester composites. Mahzan et al. [67] studied the viability of coir fiber reinforced composites in sound absorption panel. Slate [68] investigated the mechanical properties of coir fiber reinforced cement sand mortar. Geethamma et al. [69] studied the dynamic and mechanical properties of short coir reinforced natural rubber composites. Li et al. [70] reported that flexural toughness and flexural toughness index of cementitious composites with coir fiber increased by more than 10 times. Misra et al. [71] investigated fire retardant coir epoxy micro-composites. Bujang et al. [72] studied the dynamic characteristics of coir fiber reinforced composites. Biswas et al. [73] studied the effect of coir length on mechanical behaviour of coir fiber reinforced epoxy composites. It has been reported that the hardness is decreasing with the increase in fiber length up to 20 mm. Romli et al. [74] done a study on the tensile properties of coir fiber reinforced epoxy composites. In their study, the volume fraction, curing time and compression load during the solidification of composites were taken as parameters. From the results, they concluded that volume fraction significantly influences the tensile strength of the composites. Junior et al. [75] studied the tensile behaviour of coir fiber reinforced polyester composites. Coir fiber polyester composites were tested as helmets, as roofing and post-boxes [76]. Development of composite materials for buildings using coconut coir with low thermal conductivity is an interesting alternative which would solve environment and energy concern [77, 78]. These composites, with coir loading ranging from 9 to 15 wt%, have a flexural strength of about 38 MPa. Coir has also been tested as filler or reinforcement in different composite materials [79-82]. Due to lowest thermal conductivity and bulk density coconut coir gives the most interesting products. The addition of coconut coir reduced the thermal conductivity of the composite specimens and produced a lightweight product. Coir polyester composites with untreated and treated coir fibers were studied for various mechanical properties [83].

2.4 Use of Fillers in Polymer Composites

Generally, fillers are used in polymers for a variety of reasons such as cost reduction, improved processing, density control, optical effects, thermal conductivity, control of thermal expansion, electrical properties, magnetic properties, flame retardancy, improved hardness and wear resistance. Now-a-days, particulate fillers consisting of ceramic or metal particles are being used to improve the performance of polymer composites to a great extent [84]. It is reported that the effect of these fillers has significant influence on the various properties of composites. A great deal of work has been done on the use of different types of fillers in improving the performance of polymer composites. Various kinds of polymers and polymer matrix composites reinforced with metal particles have a wide range of industrial applications such as heaters, electrodes [85], composites with thermal durability at high temperature etc. [86]. Similarly, ceramic filled polymer composites have also been the subject of extensive research in last two decades. When silica particles are added into a polymer matrix, they play an important role in improving electrical, mechanical and thermal properties of the composites [87, 88]. The mechanical properties of particulate filled polymer composites depend strongly on the particle size, particle-matrix interface adhesion and particle loading. Sumita et al. [89] underlined the interest of replacing micro-scale silica by its nano-scale counterpart, since nano-scale silica particles possess superior mechanical properties. Smaller particle size yields higher fracture toughness also for calcium carbonate filled high density polyethylene [90]. Similarly, epoxy filled with smaller alumina trihydrate particles shows higher fracture toughness [91]. Thus, particle size is being reduced rapidly and many recent studies have focused on how single-particle size affects mechanical properties [92-98]. Yamamoto et al. [99] reported that the structure and shape of silica particle have significant effects on the mechanical properties such as fatigue resistance, tensile and fracture properties. Nakamura et al. [100-102] discussed the effects of size and shape of silica particle on the strength and fracture toughness based on particle-matrix adhesion and also found an increase in the flexural and tensile strength as specific surface area of particles increased. Usually, the strength of a composite strongly depends on the stress transfer between the particles and the matrix [103]. For well-bonded particles, the applied stress can be effectively transferred to the particles from the matrix resulting in an improvement in the strength. However, for poorly bonded micro-particles, reduction in strength is found to have occurred. Nicolais and Nicodemo [104] studied the effect of particle shape on tensile properties of glassy thermoplastic composites. While most of these investigations have focused either on the particle shape or on particle size, the study made by Patnaik et al. [105] reported that the mechanical properties of polyester based hybrid composites are highly influenced also by the type and content of the filler materials.

2.5 On Erosion of Polymer Composites

Solid particle erosion, a typical erosive wear mode, is the loss of material that results from repeated impact of small, solid particles. When the angle of impingement is small, the wear produced is closely analogous to abrasion. When the angle of impingement is normal to the surface, material is displaced by plastic flow or is dislodged by brittle failure. Now-a-days polymers and related composites are extensively used as structural materials in various components and engineering systems where they encounter solid particle erosion. The variables affecting the severity of erosion can be interactive and include particle size, mass, shape and velocity together with the flux of erosive particles and their angle of impact. Many investigations have been done on the solid particle erosion behaviour of polymer and polymer based composites. Polymers that have been reported in the literature include polystyrene [106], polypropylene [107, 108], nylon [109], polyethylene [110], ultra-high molecular weight polyethylene [111], polyetheretherketone [112], polycarbonate and polymethylmethacrylate [113], epoxy [114], bismileimide [115], elastomers [116, 117] and rubber [118]. Barkoula and Karger-Kocsis [119] have also presented a detailed review on important variables in erosion process and their effects on different classes of polymers and their composites. Tilly and Sage [114] tested nylon and epoxy reinforced with carbon, glass, or steel. Further, Miyazaki and Hamao [120] carried out another similar study on the erosion behaviour of short fiber reinforced thermoplastic resins with special attention focused on an incubation period of erosion. Pool et al. [16] used sand particles to erode a unidirectional continuous graphite fiber reinforced polyimide laminate, a woven graphite-fiber-reinforced epoxy laminate, a woven Aramid-fiber-reinforced epoxy laminate and a chopped-graphite-fiber reinforced poly(phenylene sulfide). Tilly [121] investigated the solid particle erosion behaviour of Nylon 66 and graphite-fiber-reinforced Nylon 66 by impingement of quartz particles. Harsha et al. [122] reported the influence of impingement angles and impact velocities on solid particle erosion of various polyaryletherketones and their composites with short fiber reinforcement. In another study, Arjula and Harsha [123] have discussed the usefulness of the erosion efficiency parameter to identify various mechanisms in solid particle erosion. This study presents extensively on the erosion response, erosion efficiency and wear mechanisms of various polymers and composites. Zahavi and Schmitt [124] investigated the erosive behaviour of sand on quartz-polyimide, glass cloth-epoxy and quartz-polybutadiene composites. Recently, few studied has been made on solid particle erosion behaviour of glass fiber reinforced polyester composites [125-129]. Miyazaki and Hamao [130] studied the effect of matrix materials, reinforcement fibers, fiber-matrix interface strength, impact angle and particle velocity on the solid particle erosion behaviour of fiber reinforced plastics. They observed that the erosion rate of a FRP decreases with the increase in the interface strength between matrix material and fibers. A study by Tewari et al [131], on the influence of impingement angles and fiber orientations concludes that unidirectional carbon and glass fiber reinforced epoxy composites show semi ductile erosion behaviour, with the maximum erosion rate occurring at 60° impingement angle. In another investigation, Barkoula and Karger-Kocsis [132] studied the effects of fiber content and relative fiber orientation on the solid particle erosion of glass fiber/polypropylene composites. It is evident from the available literature that the presence of particulate fillers has significant influence on various properties of polymer composites. But as far as the erosion behaviour of composites reinforced with both particulates and fibers is concerned, in fact, very limited work has been reported in the literature. As a result, there is no clear understanding of the mechanism of erosion in such polymer composites. Thus, a possibility that the incorporation of both particles and fibers in polymer could provide an improved wear performance has not been adequately explored so far. However, few recent publications by Patnaik et al. [126-128] on erosion wear characteristics of glass-polyester composites filled with different particulate fillers suggest that in such hybrid composites, the rate of material loss due to solid particle erosion reduce significantly with the addition of hard particulate fillers into the matrix. This improvement in the wear resistance depends on both the type and the content of filler.

2.6 On TOPSIS

TOPSIS is a MCDM approach to identify solutions from a finite set of alternatives based upon simultaneous minimization of distance from an ideal point and maximization of distance from a nadir point. TOPSIS has been applied to a number of applications by many researchers. Waigaonkar et al. [133] used TOPSIS method for resin selection in rotational molding. Sawant et al. [134] used PSI and TOPSIS method for automated guided vehicle selection. They proposed an automated guided vehicle selection index to evaluate and rank automated guided vehicle for the given application. Gadakh [135] used TOPSIS method for parametric optimization of wire electrical discharge machining. TOPSIS has been successfully applied to the areas of human resources management [136], transportation [137], product design [138], manufacturing [139], water management [140], quality control [141], and location analysis [142]. This includes a computer-aided evaluation and optimal selection procedure for robot and robot grippers [143, 144], optimal selection of motor vehicles [145], optimal selection of materials for engineering applications [146], and optimal selection of composite product system [147]. A combined TOPSIS-AHP method is used for non-traditional machining processes selection by Chakladar and Chakraborty [148]. The use of TOPSIS method to assess the mobile phone options in respect to the user's preferences order is done by Isiklar and Buyukozkan [149]. A study on customer-driven product design using AHP and TOPSIS method is done by Lin et al. [150]. A combined DEA and TOPSIS method for solving flexible bay structure layout is done by Ghaseminejad et al. [151]. It is found that this method is useful for creating, initial layout, generating initial layout alternatives and evaluating them. A MCDM approach based on ANP-TOPSIS is used to evaluate suppliers in Iran's auto industry by Shahroudi and Rouydel [152]. The selection of an optimal refinement condition to achieve maximum tensile properties of Al-15%Mg2Si composite based on TOPSIS method is done by Khorshid et al. [153]. It is observed that the TOPSIS method is considered to be a suitable approach in solving material selection problem. Singh et al. [154] studied the selection of material for bicycle chain in Indian scenario using MADM Approach. They concluded that both MADM and TOPSIS methods user friendly for the ranking of the parameters. Huang et al. [155] studied the MCDM and uncertainty analysis for materials selection in environmentally conscious design.

2.7 The Knowledge Gap in Earlier Investigations

The literature survey presented above reveals the following knowledge gap in the research reported so far:

- Though much work has been done on a wide variety of natural fibers for polymer composites, very less has been reported on the reinforcing potential of coir fiber in spite of its several advantages over others. Many low-end application areas are cited in the literature for coir based products, but there is hardly any mention of their potential use in tribological situations where synthetic fibers are widely used. Moreover, there is no report available in the literature on the erosion characteristics of coir based polymer composites.
- A number of research efforts have been devoted to the mechanical and wear characteristics of either fiber reinforced composites or particulate filled composites. However, a possibility that the incorporation of both particulates and fibers in polymer could provide a synergism in terms of improved performance has not been adequately addressed so far.
- TOPSIS method is an efficient tool for solving many MCDM problems. However, it is hardly been used for selection of composite materials based on their mechanical and erosion wear properties.

2.8 Objectives of the Present Work

The knowledge gap in the existing literature summarized above has helped to set the objectives of this research work which are outlined as follows:

1. Fabrication of a series of coir fiber reinforced epoxy composites with varying the weight percentage of fiber and fiber length.
2. To study the physical, mechanical and wear behaviour such as density, water absorption, tensile strength, tensile modulus, flexural strength, impact strength, hardness, erosion wear rate of the composites

3. To study the effect of fiber content, fiber length and Al_2O_3 filler on the physical, mechanical, water absorption and erosion wear behaviour of the composites.
4. To study the effect of impingement angle and impact velocity on the erosion wear behaviour of the composites.
5. Comparison of properties of the coir fiber reinforced epoxy composites without filler and Al_2O_3 filled coir fiber reinforced epoxy composites
6. To study the surface morphology of the eroded composite specimens in order to identify the possible wear mechanisms using SEM.
7. Ranking of composites using TOPSIS method on the basis of their physical, mechanical, water absorption and erosion wear properties.

Chapter Summary

This chapter has provided

- An exhaustive review of research works on various aspects of polymer composites reported by previous investigators
- The knowledge gap in earlier investigations
- The objectives of the present work

The next chapter describes the materials and methods used for the processing of the composites, the experimental planning and the TOPSIS method.

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Chapter 3
Materials and Methods

This chapter describes the materials and methods used for the fabrication of composites under this investigation. It presents the details of the tests related to the physical, mechanical water absorption and erosion wear characterization of the prepared coir fiber reinforced epoxy composite specimens. The methodology based on TOPSIS technique is also presented in this part of the thesis.

3.1 Materials

3.1.1 Matrix Material

Basically, composites are materials consisting of two or more chemically distinct constituents, on a macro-scale, having a distinct interface separating them. The constituents of a composite are generally arranged so that one or more discontinuous phases are embedded in a continuous phase. The primary phase of composite material having a continuous character is called matrix. The matrix phase generally comprises the bulk part of a composite. The role of matrix in a fiber reinforced composite is to transfer stress between the fibers, to provide a barrier against an adverse environment and to protect the surface of the fibers from mechanical abrasion. The matrix plays a major role in the tensile load carrying capacity of a composite structure. The binding agent or matrix in the composite is of critical importance. The matrix material in composites can be metallic, polymeric or ceramic. Polymer matrices are most commonly used because of cost efficiency, ease of fabricating complex parts with less tooling cost and they also have excellent room temperature properties when compared to metal and ceramic matrices. There are two major classes of polymers used as matrix materials such as thermoplastic and thermoset. Thermoset matrix possesses distinct advantages over the thermoplastics such as higher operating temperature, creep resistance and good affinity to heterogeneous materials [156]. Compared to thermoplastic composites, the initial low viscosity of thermoset polymers enables the higher concentration of both fillers and fibers to be incorporated in it while still holding good dispersion of filler and fiber wet-out [157]. The most common resin materials used in thermoset composites are epoxy, phenolics, vinyl ester, polyester and polyimides. Among them epoxy is the most widely used matrix due to its advantages like good adhesion to other materials, low shrinkage upon cure, good mechanical and thermal properties, good electrical insulating properties, good chemical and environmental resistance etc. [158]. Due to these advantages, epoxy (LY 556) chemically belongs to the ‘epoxide’ family, is selected as the matrix material for the present study. The epoxy resin of density 1.15 gm/cc and the corresponding hardener (HY-951) were supplied by Ciba Geigy India Ltd.

3.1.2 Fiber Material

The dispersed phase is generally harder as compared to the continuous phase and is called reinforcement. It serves to strengthen the composites and improves the overall mechanical behaviour of the composites. In polymer composites, the reinforcing phase can either be fibrous or non-fibrous (particulates) in nature. If the fibers are derived from the natural resources like plants or some other living species, they are called natural fibers. Recently, natural fibers have received considerable interest as reinforcing material for polymer based composites because of the environmental issues in combination with their low cost and some inherent interesting properties such as low density, high specific properties. A great deal of work has been done on the use of various types of natural fibers as reinforcement for polymer composites. Among all natural fibers, coir is most popular one due to its low cost, easy availability, low density, easy production and friendly to environment [7]. The lignin content in coir fiber is quite high, so the fiber becomes stiffer, tougher and long lasting when compared to other natural fibers. The coir fiber is relatively water proof and is one of the few natural fibers resistant to damage by salt water. For the current study, the coir fiber is collected from rural areas of Odisha, India. The pictorial views for collection of coir fiber used for composites shown in Figure 3.1.

Figure 3.1: Pictorial view for collection of coir fiber

3.1.3 Particulate Filler Materials

In polymer composites, variety of natural or synthetic solid particulates with organic and inorganic filler as a reinforcing material can be used. The different ceramic powders such as alumina (Al_2O_3), silicon carbide (SiC), silica (SiO_2), titania (TiO_2) etc. are widely used as conventional fillers materials. The filler materials are stronger, harder and discontinuous than matrix materials. Usually the main function of filler materials is to improve the mechanical, physical and tribological properties of the composites. In the present research work, Al_2O_3 is chosen as particulate filler material along with coir fiber. In the family of engineering ceramics, Al_2O_3 is very cost effective and widely used materials. Al_2O_3 gives better mechanical properties then other filler. The advantages of Al_2O_3 are high wear resistant, good thermal conductivity, excellent dielectric properties, high strength and stiffness. The Al_2O_3 powder with average particle size of 80-100 micron is used for the current study. Figure 3.2 shows the Al_2O_3 filler.

Figure 3.2: Al_2O_3 filler

3.2 Composite Fabrication

Coir fiber reinforced epoxy composites are fabricated using hand lay-up technique. A mould having dimension of 180 × 180 × 40 mm^3 is used for composite fabrication. The epoxy resin and the corresponding hardener are mixed in the ratio of 10:1 by weight as recommended. The filler and fibers are mixed thoroughly in the epoxy resin to minimize air entrapment. Twenty different samples C_1-C_{20} without filler and twenty samples S_1-S_{20} with constant filler content of 10 wt% were prepared by varying the length of the fiber (3 mm, 6 mm, 9 mm, 12 mm and 15 mm) and content of fiber (5 wt%, 10 wt%, 15 wt% and 20 wt%). The mould is then closed and the set-up is left to cure for 24 hours at room temperature. This cast is then post cured in the air for another 24 h after removing out of the mould. Finally, the specimens of suitable dimension are cut for physical, mechanical, water absorption and erosion test. The detail designation and composition of composites are given in Table 3.1. Figure 3.3 shows the fabricated coir fiber reinforced epoxy composites.

Table 3.1: Designation and detailed composition of the composites

Designation	Compositions
C_1	Epoxy (95%) + Coir Fiber (Fiber length 3 mm) (5%)
C_2	Epoxy (95%) + Coir Fiber (Fiber length 6 mm) (5%)
C_3	Epoxy (95%) + Coir Fiber (Fiber length 9 mm) (5%)
C_4	Epoxy (95%) + Coir Fiber (Fiber length 12 mm) (5%)
C_5	Epoxy (95%) + Coir Fiber (Fiber length 15 mm) (5%)
C_6	Epoxy (90%) + Coir Fiber (Fiber length 3 mm) (10%)
C_7	Epoxy (90%) + Coir Fiber (Fiber length 6 mm) (10%)
C_8	Epoxy (90%) + Coir Fiber (Fiber length 9 mm) (10%)
C_9	Epoxy (90%) + Coir Fiber (Fiber length 12 mm) (10%)
C_{10}	Epoxy (90%) + Coir Fiber (Fiber length 15 mm) (10%)
C_{11}	Epoxy (85%) + Coir Fiber (Fiber length 3 mm) (15%)
C_{12}	Epoxy (85%) + Coir Fiber (Fiber length 6 mm) (15%)
C_{13}	Epoxy (85%) + Coir Fiber (Fiber length 9 mm) (15%)
C_{14}	Epoxy (85%) + Coir Fiber (Fiber length 12 mm) (15%)
C_{15}	Epoxy (85%) + Coir Fiber (Fiber length 15 mm) (15%)
C_{16}	Epoxy (80%) + Coir Fiber (Fiber length 3 mm) (20%)
C_{17}	Epoxy (80%) + Coir Fiber (Fiber length 6 mm) (20%)
C_{18}	Epoxy (80%) + Coir Fiber (Fiber length 9 mm) (20%)
C_{19}	Epoxy (80%) + Coir Fiber (Fiber length 12 mm) (20%)
C_{20}	Epoxy (80%) + Coir Fiber (Fiber length 15 mm) (20%)
S_1	Epoxy (85%) + Coir Fiber (Fiber length 3 mm) (5%) +Al_2O_3 (10%)
S_2	Epoxy (85%) + Coir Fiber (Fiber length 6 mm) (5%) + Al_2O_3 (10%)
S_3	Epoxy (85%) + Coir Fiber (Fiber length 9 mm) (5%) + Al_2O_3 (10%)
S_4	Epoxy (85%) + Coir Fiber (Fiber length 12 mm) (5%) + Al_2O_3 (10%)
S_5	Epoxy (85%) + Coir Fiber (Fiber length 15 mm) (5%) + Al_2O_3 (10%)
S_6	Epoxy (80%) + Coir Fiber (Fiber length 3 mm) (10%) + Al_2O_3 (10%)
S_7	Epoxy (80%) + Coir Fiber (Fiber length 6 mm) (10%) + Al_2O_3 (10%)
S_8	Epoxy (80%) + Coir Fiber (Fiber length 9 mm) (10%) + Al_2O_3 (10%)
S_9	Epoxy (80%) + Coir Fiber (Fiber length 12 mm) (10%) + Al_2O_3 (10%)
S_{10}	Epoxy (80%) + Coir Fiber (Fiber length 15 mm) (10%) + Al_2O_3 (10%)
S_{11}	Epoxy (75%) + Coir Fiber (Fiber length 3 mm) (15%) + Al_2O_3 (10%)
S_{12}	Epoxy (75%) + Coir Fiber (Fiber length 6 mm) (15%) + Al_2O_3 (10%)
S_{13}	Epoxy (75%) + Coir Fiber (Fiber length 9 mm) (15%) + Al_2O_3 (10%)
S_{14}	Epoxy (75%) + Coir Fiber (Fiber length 12 mm) (15%) + Al_2O_3 (10%)
S_{15}	Epoxy (75%) + Coir Fiber (Fiber length 15 mm) (15%) + Al_2O_3 (10%)
S_{16}	Epoxy (70%) + Coir Fiber (Fiber length 3 mm) (20%) + Al_2O_3 (10%)
S_{17}	Epoxy (70%) + Coir Fiber (Fiber length 6 mm) (20%) + Al_2O_3 (10%)
S_{18}	Epoxy (70%) + Coir Fiber (Fiber length 9 mm) (20%) + Al_2O_3 (10%)
S_{19}	Epoxy (70%) + Coir Fiber (Fiber length 12 mm) (20%) + Al_2O_3 (10%)
S_{20}	Epoxy (70%) + Coir Fiber (Fiber length 15 mm) (20%) + Al_2O_3 (10%)

Figure 3.3: Coir fiber reinforced epoxy composites

3.3 Physical and Mechanical Tests

3.3.1 Density

The theoretical density (ρ_{ct}) of composite materials in terms of weight fractions of different constituents can easily be obtained as for the following equation given by Agarwal and Broutman [2].

$$\rho_{ct} = \frac{1}{(W_f/\rho_f) + (W_m/\rho_m)} \tag{3.1}$$

Where, W and ρ represent the weight fraction and density respectively. The suffixes f and m stand for the fiber and matrix respectively. Since the composites under this investigation consist of three components namely matrix, fiber and particulate filler, the expression for the density has been modified as

$$\rho_{ct} = \frac{1}{(W_f/\rho_f) + (W_m/\rho_m) + (W_p/\rho_p)} \tag{3.2}$$

Where, the suffix p stands for the particulate fillers. The actual density (ρ_{ce}) of the composite, however, can be determined experimentally by simple water immersion technique. The volume fraction of voids (V_v) in the composites is calculated using the following equation:

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}} \tag{3.3}$$

3.3.2 Micro-hardness

Micro-hardness measurement is done using a Leitz micro-hardness tester (Figure 3.4). A diamond indenter, in the form of a right pyramid with a square base and an angle of 136° between opposite faces, is forced into the material under a load F. The two diagonals X and Y of the indentation left on the surface of the material after removal of the load are measured and their arithmetic mean L is calculated. In the present study, the load considered F = 24.54 N and Vickers hardness number is calculated using the following equation.

$$H_V = 0.1889 \frac{F}{L^2} \tag{3.4}$$

and $L = \frac{X + Y}{2}$

Where, F is the applied load (N), L is the diagonal of square impression (mm), X is the horizontal length (mm) and Y is the vertical length (mm).

Figure 3.4: Micro-hardness tester

3.3.3 Tensile Strength

The tensile test is performed on flat specimens as per ASTM D 3039-76 using universal testing machine Instron 1195 (Figure 3.5a) at a crosshead speed of 10 mm/min. The dimension of the specimen is 150 mm × 10 mm × 4 mm and a uniaxial load is applied through both the ends. The loading arrangement is shown in Figure 3.5b. Here, the test is repeated three times on each composite type and the mean value is reported as the tensile strength of that composite.

(b) Loading arrangement for tensile test

(a) Universal testing machine Instron 1195

(c) Loading arrangement for flexural test

Figure 3.5: Universal testing machine (Instron 1195) and loading arrangement for tensile and flexural tests

3.3.4 Flexural Strength

The flexural strength of a composite is the maximum tensile stress that it can withstand during bending before reaching the breaking point. The three point bend test is conducted on all the composite samples in the universal testing machine Instron 1195. Span length of 40 mm and the cross head speed of 10 mm/min are maintained. The loading arrangement is shown in Figure 3.5c. For flexural strength, the test is repeated three times for each composite type and the mean value is reported. The flexural strength of the composite specimen is determined using the following equation.

$$\text{Flexural Strength} = \frac{3PL}{2bt^2} \tag{3.5}$$

Where, L is the span length of the sample (mm), P is maximum load (N), b is the width of specimen (mm) and t is the thickness of specimen (mm).

3.3.5 Impact Strength

Low velocity instrumented impact tests are carried out on the composite specimens. The tests are done as per ASTM D 256 using an impact tester (Figure 3.6). The pendulum impact testing machine ascertains the notch impact strength of the material by shattering the V-notched specimen with a pendulum hammer, measuring the spent energy and relating it to the cross section of the specimen. The respective values of impact energy of different specimens are recorded directly from the dial indicator.

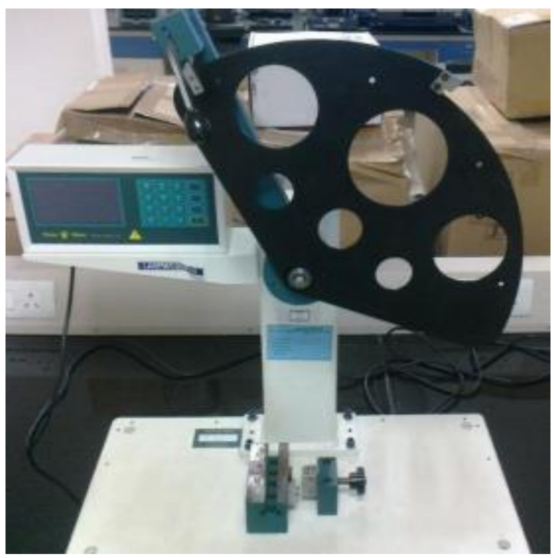

Figure 3.6: Izod impact testing machine

3.4 Scanning Electron Microscopy

The surfaces of the specimens are examined directly by scanning electron microscope JEOL JSM-6480LV (Figure 3.7). The composite samples are mounted on stubs with silver paste. To enhance the conductivity of the samples, a thin film of platinum is vacuum-evaporated onto them before the photomicrographs are taken.

Figure 3.7: Scanning Electron Microscope (JEOL JSM-6480LV)

3.5 Water Absorption Test

The water absorption tests of coir fiber reinforced epoxy composites are performed as per ASTM 570. The weight of the samples was taken before subjecting them to normal water. The specimens were weighed regularly at 24, 48, 72, 96, 120, 144, 168, 192, 216, 240, 264, 288, 312, 336, 360, 384 and 408 hours. After exposure for 24h, the specimens were taken out from the moist environment and all surface moisture was removed with a clean dry cloth. The specimens were reweighed to the nearest 0.001 mg within 1 min of removing them from the environment chamber. The percentage weight gain of the samples was measured at different time intervals by using the following equation:

$$Wa\ (\%) = \frac{w_2 - w_1}{w_1} \times 100 \tag{3.6}$$

Where, w_2 is the weight of specimen at a given immersion time and w_1 is the oven-dried weight.

3.6 Erosion Test

The solid particle erosion experiments were carried out as per ASTM G76 on the erosion test rig as shown in Figure 3.8. The schematic diagram is shown in Figure 3.9. Erosion test rig consists in different components such as an air drying unit, an air compressor, a conveyer belt type particle feeder, an air particle mixing and accelerating chamber. The dried and compressed air is then mixed with silica sand and the sand size obtained was 200 ± 50 microns, which was fed constantly by a conveyer belt feeder into the mixing chamber and then accelerated by passing the mixture through a convergent brass nozzle of 4 mm internal diameter. Samples of composite were held at selected impingement angles as (30°, 45º, 60°, 75° and 90°) and impact velocity as (48, 70, 82 and 109 m/s).). In the experimental work, silica sand was used as an erodent. The distance between the target material and nozzle was approximately 10 mm. The samples were cleaned in acetone before and after in each test. After testing the eroded samples were cleaned with a brush to remove fine sand particles attached to the surface then the weight of sample are measured by precision electronic balancing machine and an accuracy is ± 0.1 mg. The loss of weight was recorded for subsequent calculation of erosion rate. This procedure has been repeated until the erosion rate attains a constant steady-state value. The erosion rate (E) is expressed in equation:

$$E = \frac{\Delta_w}{w_e} \tag{3.7}$$

Where, 'Δw' is the mass loss at test sample in gm. and 'w_e' is the mass of eroding particles (i.e., testing time × particle feed rate). The experimental parameters for steady state erosion test are expressed in Table 3.2.

Table 3.2: Experimental parameters for steady state erosion test

Erodent	Silica sand
Erodent size (µm)	200 ± 50
Impingement angle (°)	30, 45, 60, 75 and 90
Impact velocity (m/s)	48, 70, 82 and 109
Stand-off distance (mm)	10
Time of experiment (min)	10
Feed rate	2.5-3.0 g/min
Test temperature	Room temperature

Figure 3.8: Solid particle erosion test set up (1) sand hopper, (2) conveyor belt system for sand flow, (3) pressure transducer, (4) particle-air mixing chamber, (5) nozzle, (6) x–y and h axes assembly, (7) sample holder.

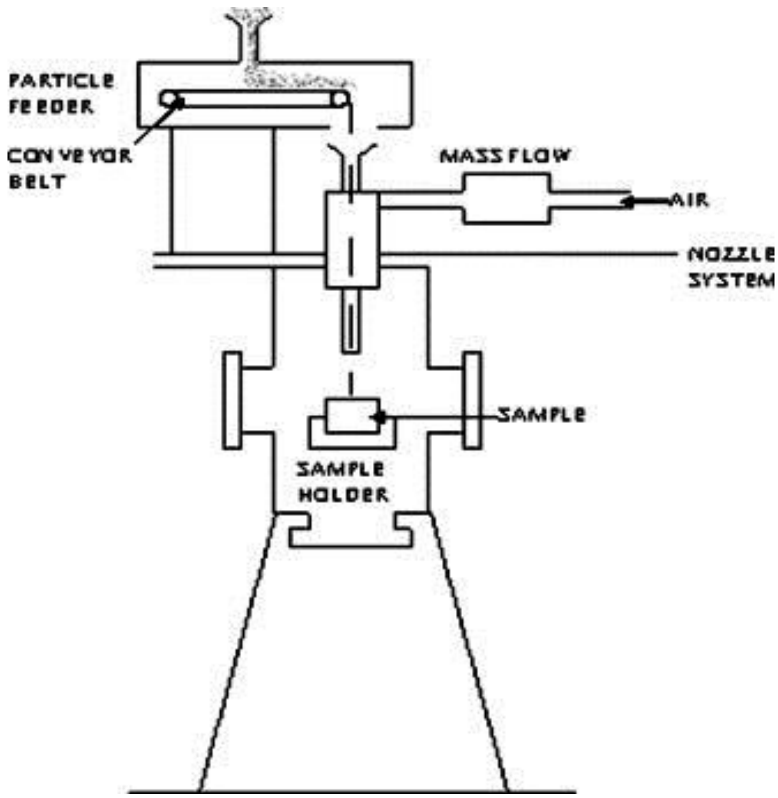

Figure 3.9: Schematic diagram of an erosion test rig

3.7 TOPSIS Method

TOPSIS method is one of the best methods of MCDM approaches. This method was first presented in the year 1981 by Hwang & Yoon. The main concept of this method is select the alternative should have nearest to the positive ideal solution and farthest from the negative ideal solution. But the positive ideal solution is increasing the benefit criteria and decreases the cost criteria. However, the negative ideal solution is increasing the cost criteria and decreases the benefit criteria [159, 160]. Generally, the TOPSIS method is used for estimating the materials ranking. Many research are introduce the TOPSIS concept because to improve MCDM and solve in different problems. In the present research work TOPSIS method is used to rank the fabricated composites materials as it offers a number of benefits. The ranking is done based on mechanical, physical and erosion wear properties of composite materials such as density, tensile strength, tensile modulus, flexural strength, hardness, impact strength, water absorption and erosion wear rate. The steps for the weighting and ranking process using TOPSIS method are mentioned below [161]:

Step-1: The overall TOPSIS decision matrix (DM) is expressed in matrix format as,

$$DM = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ . \\ . \\ . \\ A_m \end{array} \begin{array}{c} \begin{array}{cccccccc} C_1 & C_2 & C_3 & . & . & . & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & x_{13} & . & . & . & x_n \\ x_{21} & x_{22} & x_{23} & . & . & . & x_{1n} \\ x_{31} & x_{32} & x_{33} & . & . & . & x_{2n} \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ x_{m1} & x_{m2} & x_{m3} & . & . & . & x_{mn} \end{bmatrix} \end{array} \tag{3.8}$$

Where A_1, A_2 and A_3....A_m are feasible alternatives out of which decision makers have to choose, C_1, C_2 and C_3.... C_n are the criteria with which alternative performance are measured; x_{ij} is the rating of alternative A_i with respect to criterion C_j, w_j is the weight of criterion C_j.

Step 2: Determine the normalized decision matrix and the normalized value n_{ij} using the following formula,

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x^2_{ij}}} \tag{3.9}$$

Where, i = 1, 2, 3,…. m; and j = 1, 2, 3,….n

Step 3: Calculate the weighted normalized decision matrix and weighted normalized value v_{ij} using the formula,

$$v_{ij} = w_j \times n_{ij} \tag{3.10}$$

Where, w_j is the relative weight of the i^{th} criteria or attribute, and

$$\sum_{j=1}^{m} w_j = 1 \tag{3.11}$$

Step 4: Calculate the positive ideal solutions and negative ideal solutions using following equations,

$$A^+ = \{v_1^+, v_2^+, v_3^+ ....., v_m^+\} \tag{3.12}$$

$$= \left\{ \left(\max_j v_{ij} \;/\; j \in \Omega_b \right), \left(\min_j v_{ij} \;/\; j \in \Omega_c \right) \right\}$$

$$A^- = \{v_1^-, v_2^-, v_3^- ....., v_m^-\}$$

$$(3.13) = \left\{ \left(\min_j v_{ij} \;/\; j \in \Omega_b \right), \left(\max_j v_{ij} \;/\; j \in \Omega_c \right) \right\} \tag{3.13}$$

Where, Ω_b and Ω_c both are related with beneficial attribute and non-beneficial attributes respectively.

Step 5: Determine the separation measure value using the n-dimensional Euclidean distance method. The separation of each alternative from the ideal solution is expressed as:

$$d^{+}=\sqrt{\sum_{j=1}^{n}\left(v_j^{+}-v_{ij}\right)^2} \qquad (3.14)$$

Where, i =1, 2, 3, …..m

Similarly, the separation from the negative-ideal solution is expressed as:

$$d^{-}=\sqrt{\sum_{j=1}^{n}\left(v_j^{-}-v_{ij}\right)^2} \qquad (3.15)$$

Where, i = 1, 2, 3, …..m

Step 6: Calculate the relative closeness to the ideal solution and the relative closeness of the alternative A_i with respect to A^+ using the following formula,

$$cl_i^{+}=\frac{d_i^{-}}{d_i^{+}+d_i^{-}} \qquad (3.16)$$

Where, i = 1, 2, 3, …..m

Step 7: Finally, rank the preference order. A large value of closeness coefficient cl_i^+ indicates a good performance of the alternative A_i and the best alternative is the one with the higher closeness value.

Chapter Summary

This chapter has provided:

- Details of the materials used along with fabrication process.
- Different testing methods used or examining the physical, mechanical, water absorption and erosion wear behaviour of composites.
- Details of TOPSIS methodology used for ranking of materials.

The next chapter refers to the results and discussion of the physical, mechanical, water absorption and erosion wear behaviour of composites.

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Chapter 4
Results and Discussion: Physical, Mechanical and Water Absorption Behaviour of Composites

This chapter presents the physical, mechanical and water absorption behaviour of the coir fiber reinforced epoxy composites. The effect of fiber length and content on various properties of composites is discussed. Morphological analysis is done to observe the fracture behaviour of the composite samples after tensile and flexural tests using scanning electron microscope. These results are compared with those of a similar set of coir fiber reinforced composites filled with Al_2O_3 particulate filler. The effect of the filler on the properties of the composites has also been discussed.

4.1 Physical and Mechanical Properties of Composites

4.1.1 Density and void content

Density of a composite material depends on the relative proportion of reinforcement and matrix and is one of the most important factors in determining the properties of composites. The void content of composites is the difference between the experimental density and the theoretically density values of composites. The effect of fiber content and fiber length on the density of composites is shown in Figure 4.1. It is observed from the figure that the density of composites decreases as the fiber length increases from 3 mm to 15 mm. This is due to the fact that the inclusion of long fibers into the composites decreases the packing, which leads to the disruption of fiber distribution and resulting in high void spaces. Apparently, greater void contents yield low density composite. It is also observed that the short fibers are aligned and pack densely than the longer ones [77]. On the other hand, the density of composites increases with increase in fiber content. Variation of void content with fiber content and fiber length is shown in Figure 4.2. It can be seen that the void content in the composites increases with the increase in fiber content. Presence of large amounts of the hydroxyl group in natural fibers makes them polar and hydrophilic in nature; on the other hand most polymers are hydrophobic in nature. This polar nature also results in high moisture absorption in natural fiber based polymer composites, leading to fiber swelling and voids in the fiber-matrix interface [162].

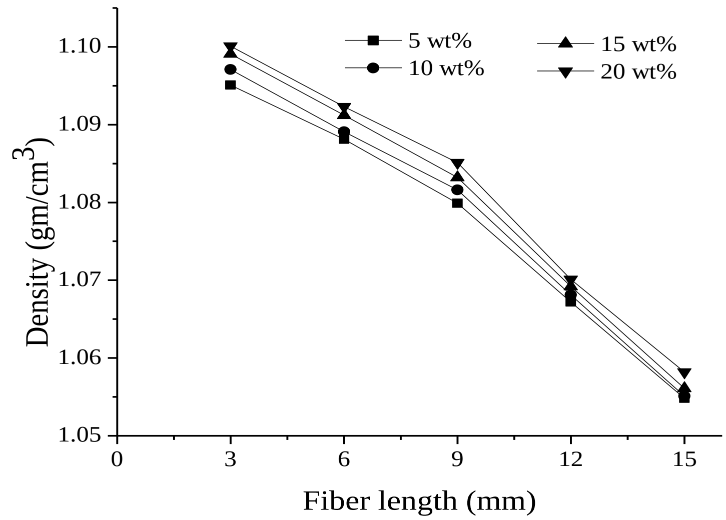

Figure 4.1: Effect of fiber content and fiber length on density of composites

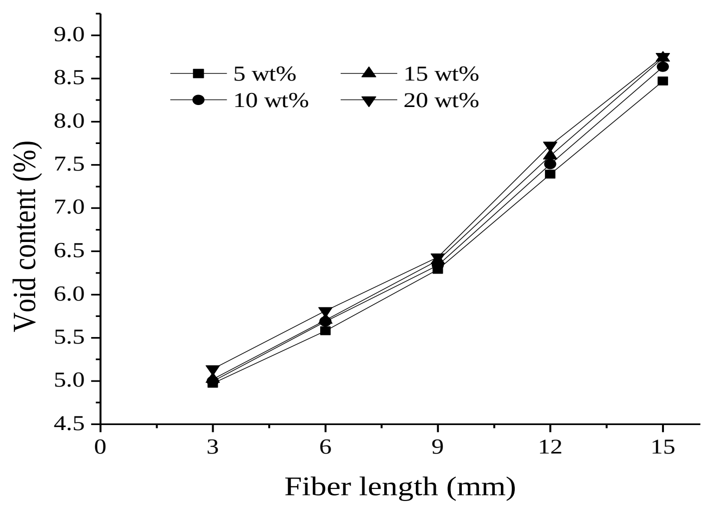

Figure 4.2: Effect of fiber content and fiber length on void content of composites

Figure 4.3 shows the effect of fiber parameters on the density of coir fiber reinforced composites filled with Al_2O_3 particulate filler. It is clearly observed from the figure that the density of composites decreases as the fiber length increases from 3 mm to 15 mm. At 3 mm fiber length, the composite increases the packing, which leads to the proper fiber distribution and resulting in less void spaces. It is also observed that with the addition of filler, there is not significant decrease in density of composites at 6 mm length as compared to composites at 3 mm length. The reason may be due to the fact that the 6 mm length may not be substantial long to cause fiber entanglement which leads to the formation of voids. Another possible reason may be due the presence filler which hinders the decrease in density value up to 6 mm fiber length. However, further increase in fiber length, the density value decreases significantly. It is also clearly observed from the figure that the density of composites increases with increase in fiber content. Figure 4.4 shows the variation of void content with fiber parameters. It is evident from the figure that the void content in the composites increases with the increase in fiber content as in case of composites without filler. However, composites with filler reduce the void content as compared to unfilled one. This is because the filler fills in the gap between the fiber and the matrix and, due to the dense structure, the chances of entrapment of air reduces, which in turn reduces the presence of pores and voids [163]. It is also observed from the figure that the void content increases with the increase in fiber length. However, the increase in void content for composites with 6 mm fiber length as compared to composites with 3 mm fiber length is not substantial. The reason may be due to the filler reduces the void content of the composites in both the cases.

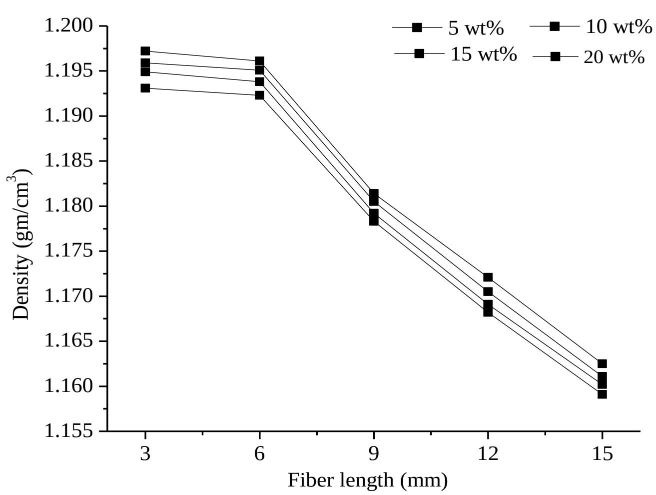

Figure 4.3: Effect of fiber content and fiber length on density of composites filled with Al_2O_3 filler

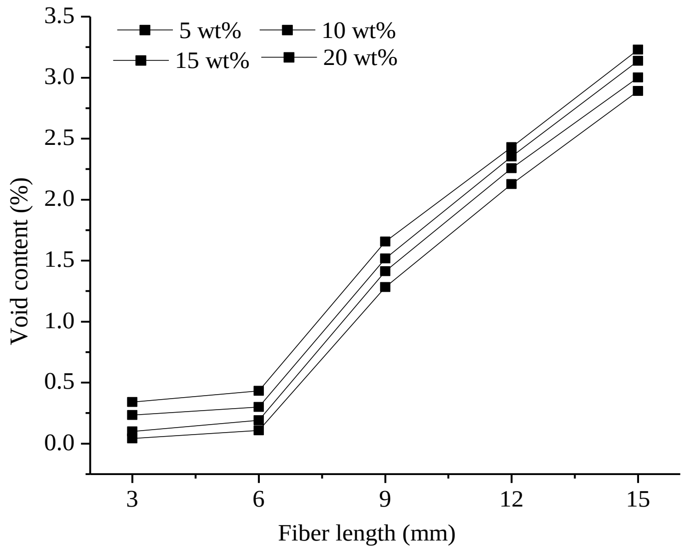

Figure 4.4: Effect of fiber content and fiber length on void content of composites filled with Al_2O_3 filler

4.1.2 Tensile properties

The effect of fiber length and fiber content on the tensile properties of coir fiber reinforced epoxy composites is shown in Figure 4.5 and Figure 4.6. The tensile strength of composites increases with increase in the fiber content up to 15 wt% and then decreases with further increase in the fiber content. This decrease may be due to the improper adhesion hinders the increase of tensile strength. As the fiber content increases, instead of dispersion the gathering of fibers takes place and the resin cannot wet the fibers due to non-entrance of resin in-between the two adjacent fibers. The chances of failure increase with the increase in fiber to fiber interaction. It is clearly observed from the Figure 4.5 that as the fiber length increases, the tensile strength of composites increases and then decreases irrespective of fiber content. Generally, fiber length has significant influence on the properties of composites. In addition to holding the fibers together, matrix has an important function of transferring applied load to the fibers. The efficiency of a fiber reinforced polymer composite depends on the ability to transfer stress from the matrix to the fiber and the fiber-matrix interface [164]. In case of small fiber length, tensile strength is less due to the fact that length may not be sufficient enough for proper distribution of load. On the other hand, for the composites of longer fiber length, tensile strength decreases. The reason may be due to the fact that longer fiber may not become compatible with the matrix properly. Therefore, improper bonding occurs between the fibers and the matrix. Furthermore, fibers may be folded and there is no bonding between the unfolded and folded portion of fiber which resulted in a lower strength. The reduction of strength may be due to the fiber entanglement. The maximum tensile strength of 24.71 MPa is observed for composites with 12 mm fiber length and 15 wt% fiber content. This result is in well agreement with that obtained by Ojha et al. [165] in orange peel reinforced polymer composite. The tensile strength of short banana fiber reinforced epoxy composite was observed 16.39 MPa at 5 mm fiber length and 12 wt% of fiber loading [166, 167]. Figure 4.6 depicts the effect of fiber length as well as fiber content on the tensile modulus of coir fiber reinforced epoxy composites. It can be observed that the tensile modulus increases with the increase in fiber content irrespective of fiber length. Generally, the increase in fiber content results in increased brittleness of the composites; thus stress/strain curve becomes steeper [168]. The poor interfacial bonding between fiber and matrix creates partially separated micro spaces that obstruct the stress propagation among them. Thus, as the fiber content increases, the degree of hindrance increases, which in turn increases the stiffness. The stress/strain curve for coir fiber reinforced composites without filler is shown in Figure 4.7. The tensile modulus of the composites also increases with the increase in fiber length. Similar trend is also observed by the previous researchers [169, 170]. The maximum tensile modulus of 2.27 GPa is obtained for composites with 15 mm fiber length and 20 wt% fiber content. The tensile modulus of short banana fiber reinforced epoxy composite was observed 0.652 GPa at 5 mm fiber length and 12 wt% of fiber loading [166]. Mohammed et al. [171] observed the tensile modulus of oil palm fiber /epoxy composites was 1.342 GPa at 30 wt% of fiber loading. The tensile strength of Al_2O_3 filled coir fiber reinforced epoxy composites is presented in Figure 4.8. Similar trend of increase in tensile strength with increases in fiber content up to 15 wt% is observed for composites with Al_2O_3 filler. However, further increase in fiber content the strength decreases. An increase in tensile strength is observed for the composite with 10wt% of filler content as compared to composites without filler. This may be due to good particle dispersion and strong polymer/filler interface adhesion for effective stress transfer. It is also observed that as the fiber length increases, the tensile strength of composites increases and then decreases irrespective of fiber content. Maximum tensile strength of 25.71 MPa is observed for Al_2O_3 filled composites with fiber loading of 15 wt% and fiber length of 12 mm. The effect of fiber parameters on the on the tensile modulus of composites is shown in Figure 4.9. It is evident from the figure that the tensile modulus increases with the increase in fiber content. On the other hand as the fiber length increases, the tensile modulus of the composites also increases. It is also observed that Al_2O_3 filled coir fiber composites shows better tensile properties as compared to unfilled one.

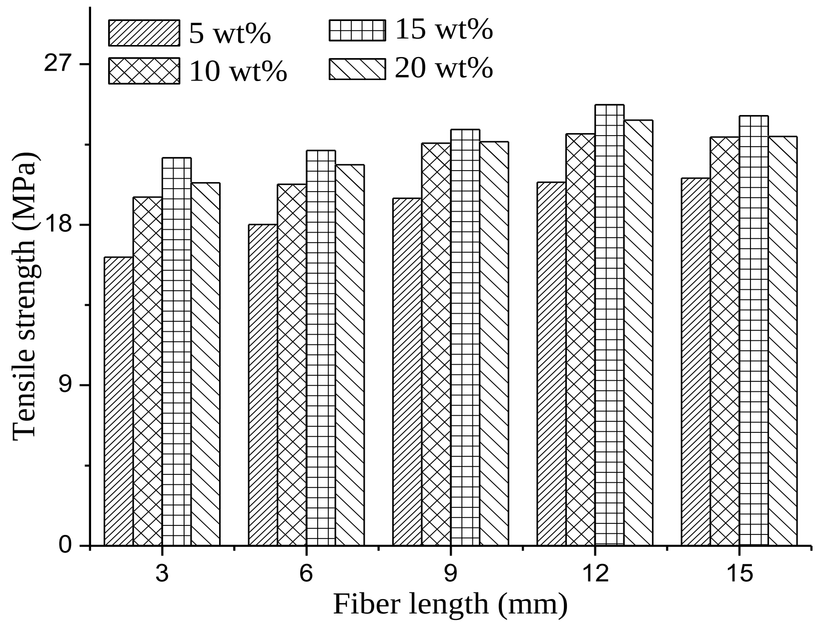

Figure 4.5: Effect of fiber content and fiber length on tensile strength of composites

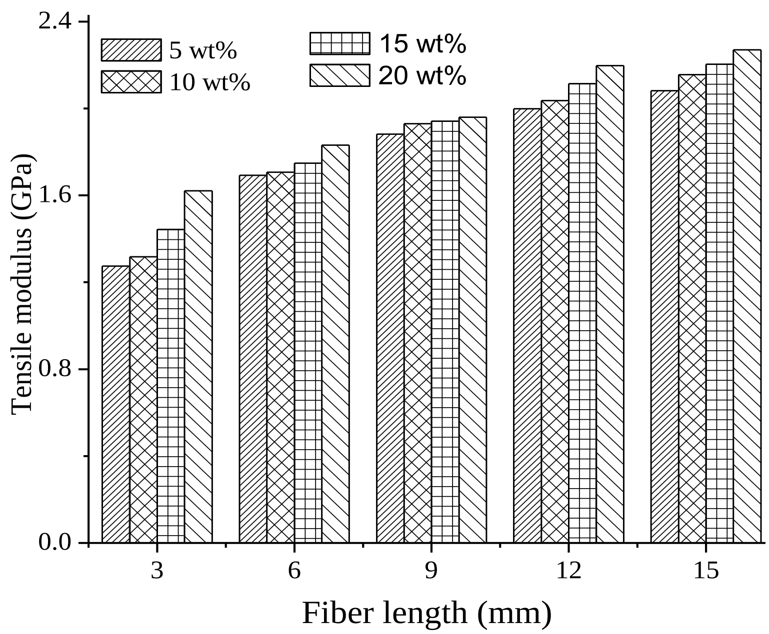

Figure 4.6: Effect of fiber content and fiber length on tensile modulus of composites

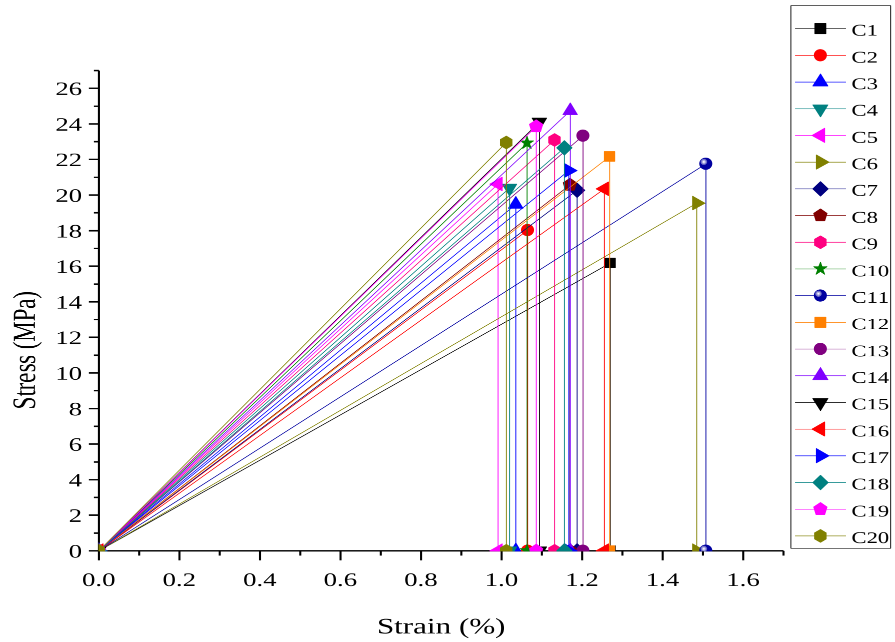

Figure 4.7: Stress/strain curve for coir fiber reinforced epoxy composites without filler

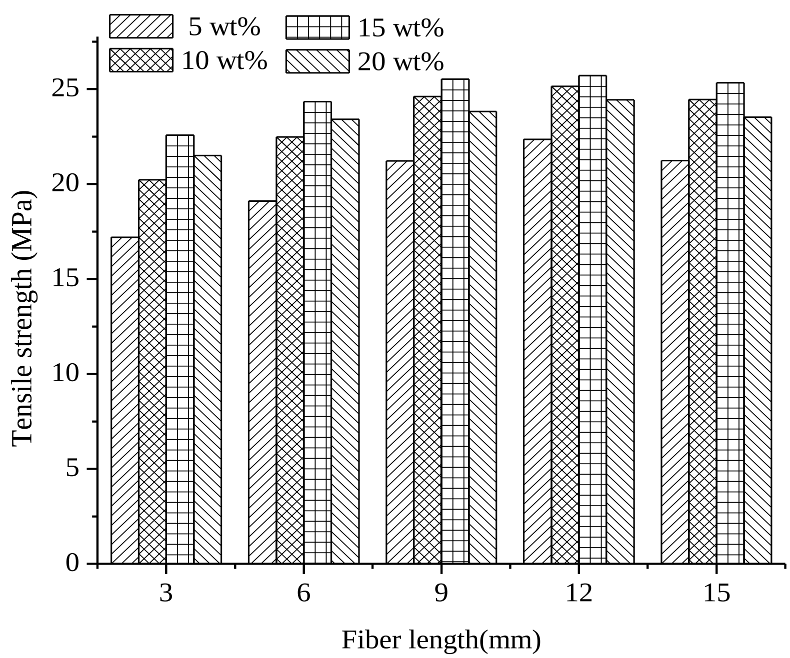

Figure 4.8: Effect of fiber content and length on tensile strength of composites filled with Al_2O_3 filler

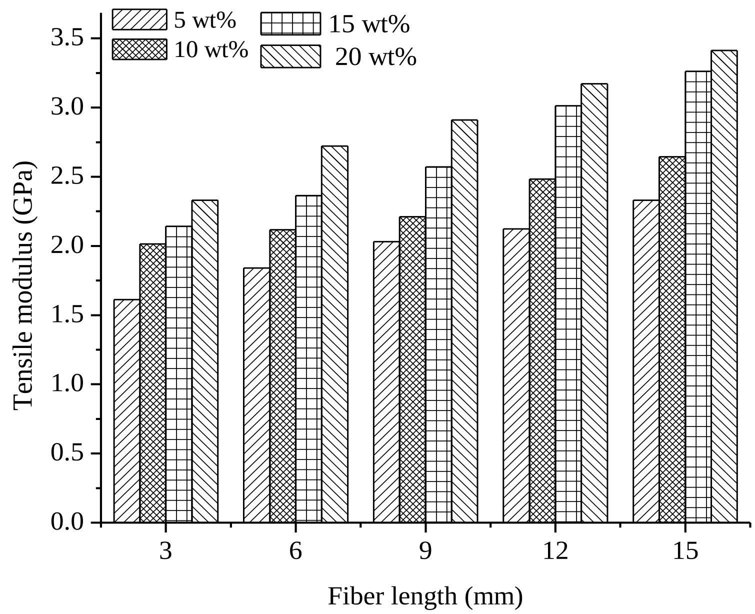

Figure 4.9: Effect of fiber content and length on tensile modulus of composites filled with Al_2O_3 filler

4.1.3 Flexural strength

Flexural strength of coir epoxy composites at different fiber content and fiber length is shown in Figure 4.10. It is observed from the figure that the flexural strength increases with increase in fiber content up to 15 wt%, and then it decreases. It follows the similar trend as tensile behaviour. It substantiates that tensile force has a greater influence on flexural properties than the compressive force. The reasons for the lower flexural properties at higher fiber content are probably due to the weak fiber-to-fiber interaction, void and poor dispersion of fiber in the matrix [172, 173]. Similar observation has been reported in case of short banana fiber reinforced epoxy composites by the previous researchers [174]. The maximum flexural strength of 29.43 MPa is obtained for composites with 12 mm fiber length and 15 wt% fiber content. The flexural strength of sisal fiber reinforced epoxy composite was observed 22.3 MPa at 20 % volume fraction of fiber [175]. It is also observed from the figure that as the fiber length increases, the flexural strength of composites increases and then decreases. The effect of fiber content and fiber length on the flexural strength of composites is shown in Figure 4.11. The similar trend of increase in flexural strength with increase in fiber content up to 15 wt% is also observed in case of composites with Al_2O_3 filler.

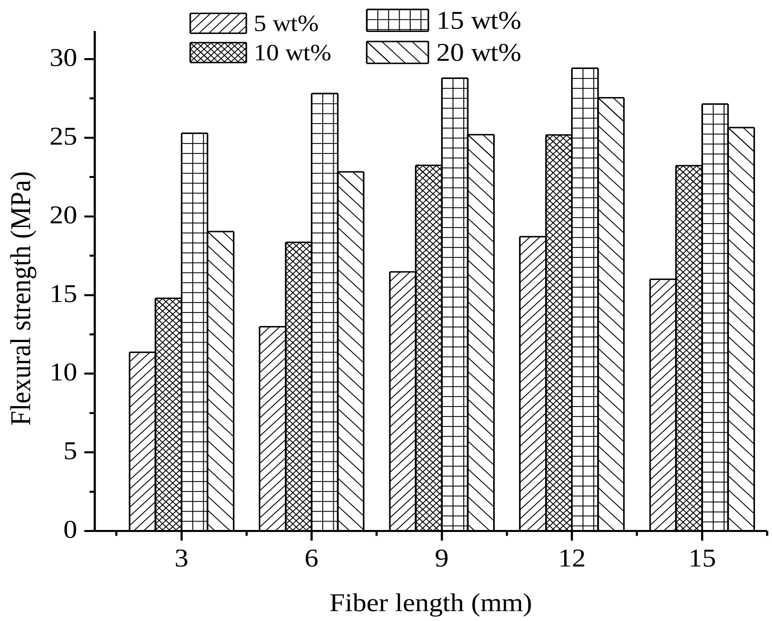

Figure 4.10: Effect of fiber content and fiber length on flexural strength of composites

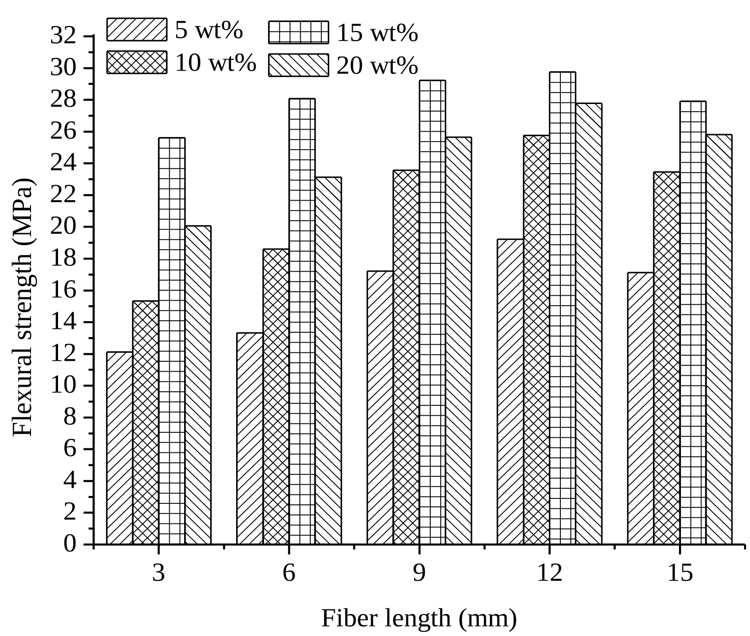

Figure 4.11: Effect of fiber content and fiber length on flexural strength of composites filled with Al_2O_3 filler

The effect of fiber length on flexural strength of composites with filler shows similar trend of composites without filler. The increase in the flexural properties in Al_2O_3 filled composites (up to 10 wt% filler) may be attributed to the reason that the filler offers greater resistance to crack initiation and propagation in the composite [176]. The maximum flexural strength of 29.75 MPa is observed for Al_2O_3 filled composites with 12 mm fiber length and 15 wt% fiber content.

4.1.4 Hardness

The effect of fiber content and fiber length on the micro-hardness of composites is shown in Figure 4.12. Generally, hardness is a function of the relative fiber content and modulus of the composites. The fibers that increase the moduli of composite materials should also increase the hardness. It is observed from the figure that as the weight percentage of fiber in the composite increases, the hardness of composite also increases. Similarly, as the fiber length increases, the hardness of the composite also increases. Similar trend of increase in hardness of the composites with increase in fiber length has also been reported by the researchers [177]. The maximum hardness of 18.61 Hv is observed for composites with 15 mm fiber length and 20 wt% fiber content. This result is consistent with the previous researcher in orange peel reinforced polymer composites [165].

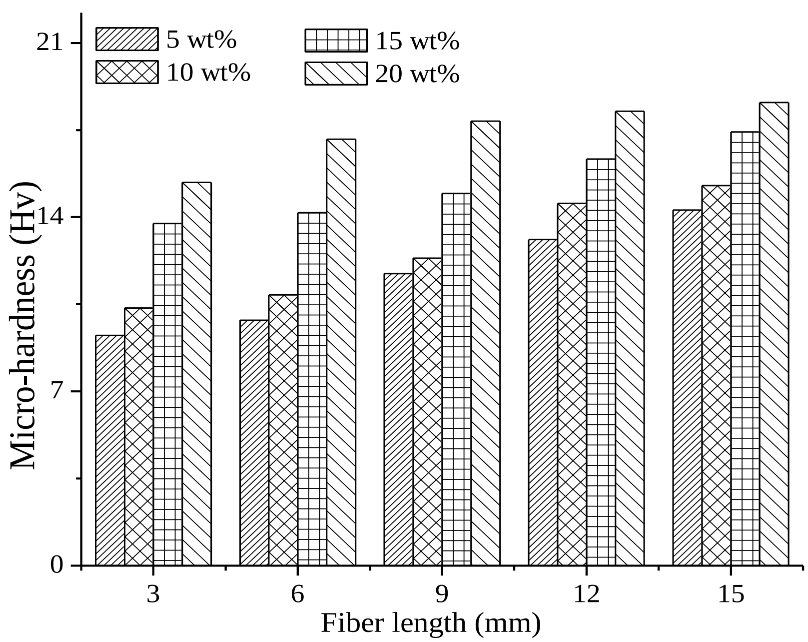

Figure 4.12: Effect of fiber content and fiber length on micro-hardness of composites

Figure 4.13 shows the effect of fiber content and fiber length on the micro-hardness of Al_2O_3 filled composites. The increase in hardness value with the increase in both the fiber content and fiber length is clearly observed from the Figure 4.13. It is also evident from the figure that the improvement in hardness property with the addition of Al_2O_3 filler as compared to unfilled one. The addition of filler content increases the hardness of composite material due to increase in the resistance strength of polymer to plastic deformation. In this case, the polymeric matrix phase and the solid filler phase would be pressed together and touch each other more tightly [178]. The maximum hardness value of 19.52 Hv is observed from composites with 20 wt% fiber loading and 15 mm fiber length.

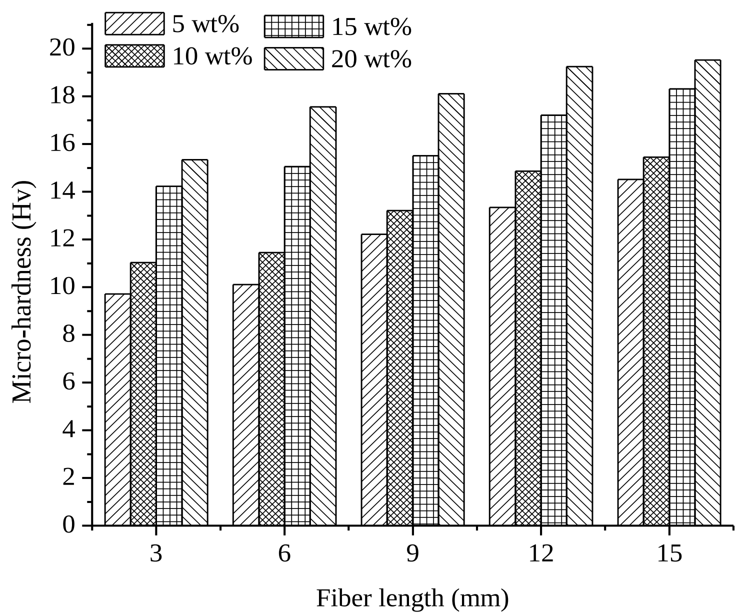

Figure 4.13: Effect of fiber content and fiber length on micro-hardness of composites filled with Al_2O_3 filler

4.1.5 Impact strength

The effect of fiber content and fiber length on the impact strength of composites is shown in Figure 4.14. It is observed that the impact strength increases with the increase in fiber content up to 15 wt% and then decreases. Generally, the impact strength of fiber reinforced polymeric composites depends on the type of fiber, polymer and fiber-matrix interfacial bonding. Also, it has been reported that high fiber content increases the probability of fiber agglomeration and its stress concentration requiring less energy for crack propagation. The impact strength of all composites increased with fiber content up to 15 wt%. The reasons are that the fiber is capable of absorbing energy and compression pressure which removes the voids contents in the composites because of appreciative mix-up fiber and matrix.

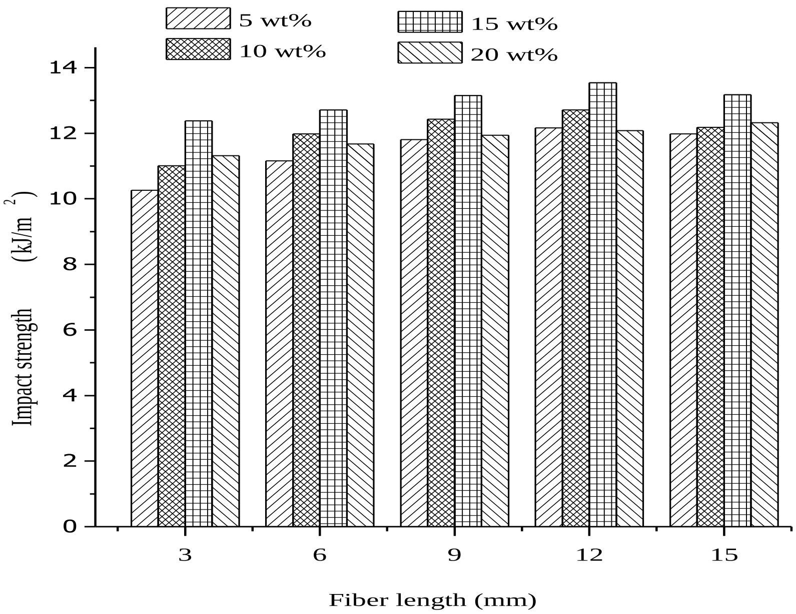

Figure 4.14: Effect of fiber content and fiber length on the impact strength of composites

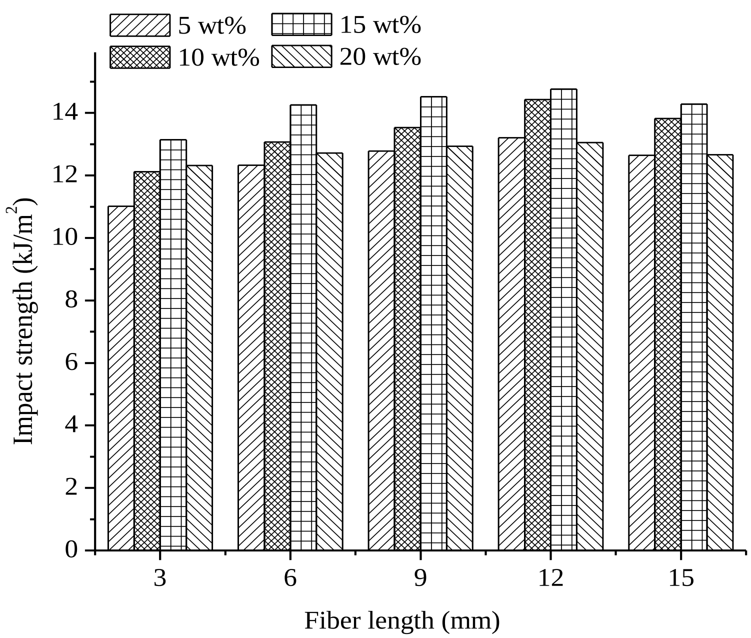

Figure 4.15: Effect of fiber content and fiber length on impact strength of composites filled with Al_2O_3 filler

Figure 4.14 also shows that the increase in impact strength of composites improves with the increase in fiber length. The reason may be due to the interface bonding, nature of constituent between the fiber and matrix [179, 167]. The maximum impact strength of 13.54 kJ/m^2 is obtained for composites with 12 mm fiber length and 15 wt% fiber content. Figure 4.15 shows the effect of fiber content and fiber length on the impact strength of Al_2O_3 filled composites. Similar trend of increase in impact strength with the increase in fiber content up to 15 wt% is observed. It is also observed that Al_2O_3 filled composites shows better impact property as compared to unfilled composites. The presence of filler leads to a higher impact strength due to the interfacial reaction and provides an effective barrier for pinning and bifurcation of the advancing cracks [180]. The maximum impact strength of 14.76 kJ/m^2 is obtained for composites with 12 mm fiber length and 15 wt% fiber content.

4.2 Water Absorption Behaviour

Water is one of the environmental factors that mostly influence the behaviour of fiber reinforced polymer composites. Natural fibers as reinforcement have been limited by their susceptibility to water absorption, due to their chemical composition being rich in cellulose, hydrophilic in nature. The water absorption by the composites containing natural fibers had several adverse effects on their properties and affected their long-term performance. The water absorption can lead to swelling of the fiber, forming voids and micro-cracks at the fiber-matrix interface region which may result in a reduction of the mechanical properties and dimensional stability of composites. Several studies in the use of natural fiber reinforced polymeric composites have reported that water molecules act as a plasticiser agent in the composite material, which normally leads to a decrease in the mechanical properties of the composites after water absorption [181]. In order to promote the wider use of such materials in high-performance applications, it is essential to consider the effect of moisture absorption and water uptake on their physical and mechanical properties. Water absorption test is done to determine the percentage of water absorbed under specified conditions. The effect of fiber content and fiber length on the water absorption of the coir fiber reinforced epoxy composites with increase in immersion time is shown in Figures 4.16-4.23. Figures 4.16-4.19 show the effect of fiber parameters on the water absorption behaviour of the coir fiber reinforced epoxy composites without filler. In all cases, the water absorption process is sharp at the beginning and leveled off for some length of time where it approaches to equilibrium. Figure 4.16 show the rate of water absorption of coir fiber reinforced epoxy composites at fiber content of 5 wt%. Similarly, the water absorption behaviour of coir fiber reinforced epoxy composites at fiber content of 10 wt%, 15 wt% and 20 wt% are shown in Figure 4.17, Figure

4.18 and Figure 4.19, respectively. It is observed from the figures that the rate of water absorption increased from 2.98 % to 13.6 % for 3 mm to 15 mm fiber lengths at 5 wt% and 20 wt% fiber content, respectively.

Similarly, it is also observed from the figure that the rate of water absorption increases with increase in fiber content. Composites with 20 wt% coir fiber content shows more water absorption rate as compared to 5 wt% fiber content irrespective of fiber length as can be observed from Figure 4.16 and Figure 4.19. The reason for increased water absorption percentage may be due to higher hydrophilic nature of cellulosic fibers, presence of voids and micro cracks present inside the composite. Similar trend is also observed by previous researchers for jute fiber reinforced epoxy composites [182]. Similarly, the minimum water absorption rate is observed for composites with 5 wt% fiber content and at 3 mm fiber length. Generally, the rate of water absorption is greatly affected by the composite's density and void content. Also, longer the fiber, the higher is the water absorption [78]. Similarly, the effect of fiber content and fiber length on the water absorption behaviour of the Al_2O_3 filled coir fiber reinforced epoxy composites with increase in immersion time is shown in Figures 4.20-4.23. Figure 4.20 show the water absorption behaviour of Al_2O_3 filled coir fiber reinforced epoxy composites at fiber content of 5 wt%. Similarly, the corresponding figures for composites with fiber content of 10 wt%, 15 wt% and 20 wt% are shown in Figure 4.21, Figure 4.22 and Figure 4.23, respectively. Similar trend of increase in the rate of water absorption with the increase in fiber content and fiber length is observed for Al_2O_3 filled composites. It is also evident from the figures that the rate of water absorption is less in case of Al_2O_3 filled composites as compared to unfilled one. Al_2O_3 filled composites with 5 wt% of fiber content and 3 mm fiber length shows minimum water absorption rate as compared to all other types of composites under the present study.

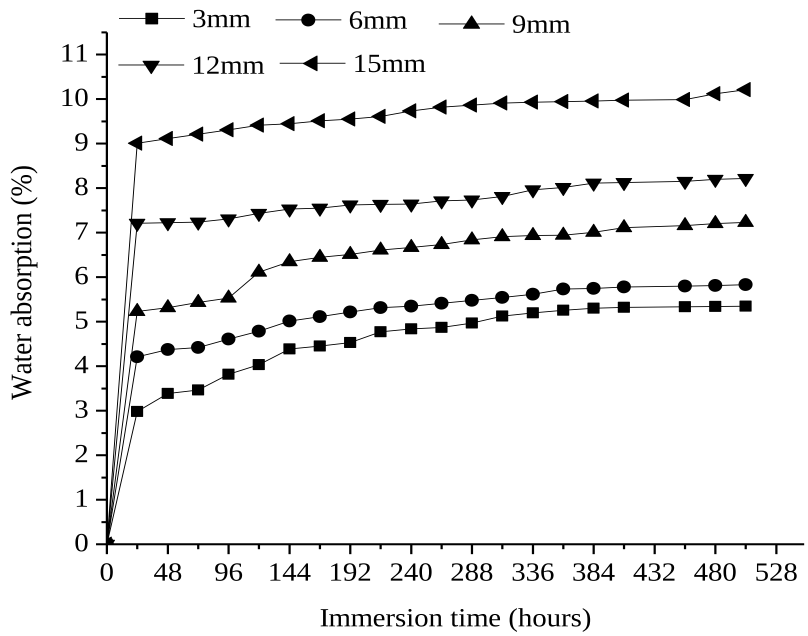

Figure 4.16: Water absorption behaviour of coir fiber reinforced epoxy composites with 5 wt% fiber content

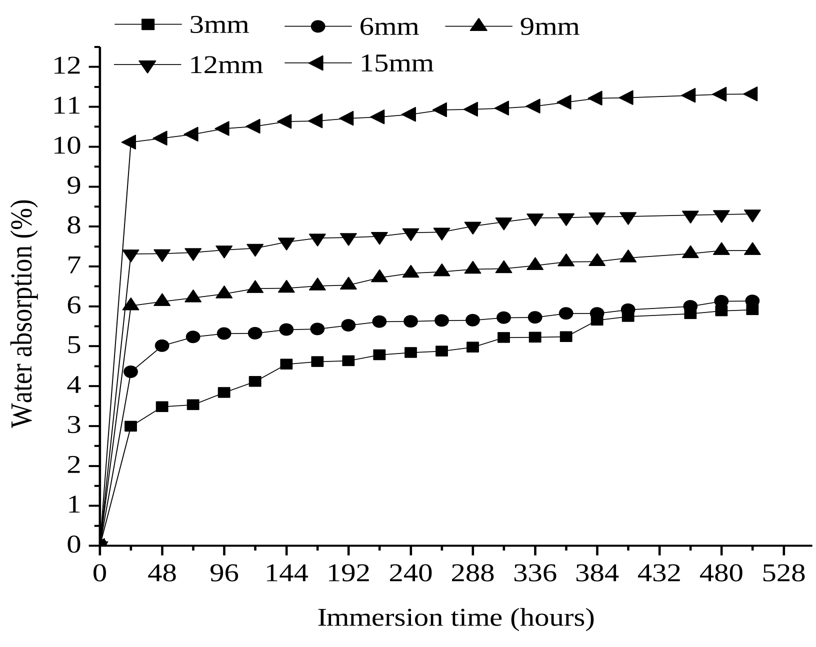

Figure 4.17: Water absorption behaviour of coir fiber reinforced epoxy composites with 10 wt% fiber content

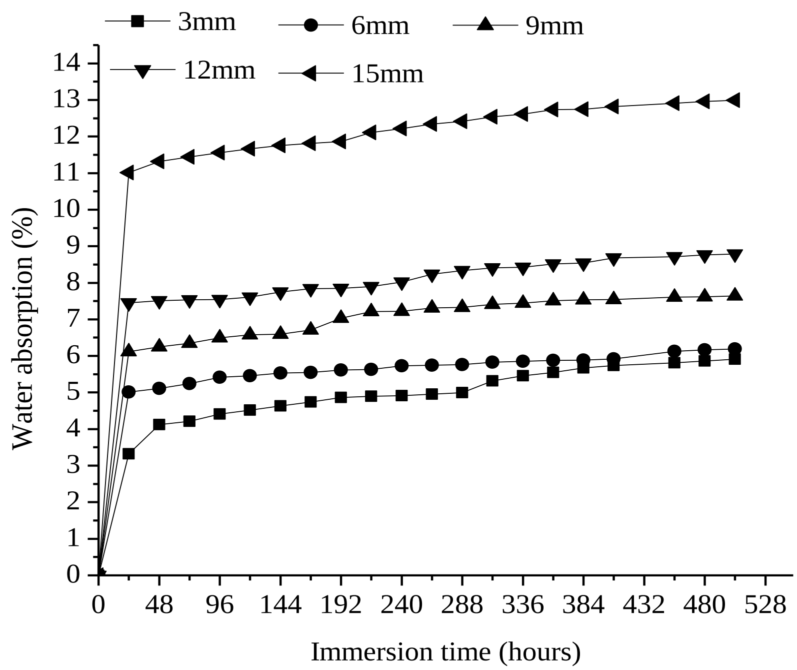

Figure 4.18: Water absorption behaviour of coir fiber reinforced epoxy composites with 15 wt% fiber content

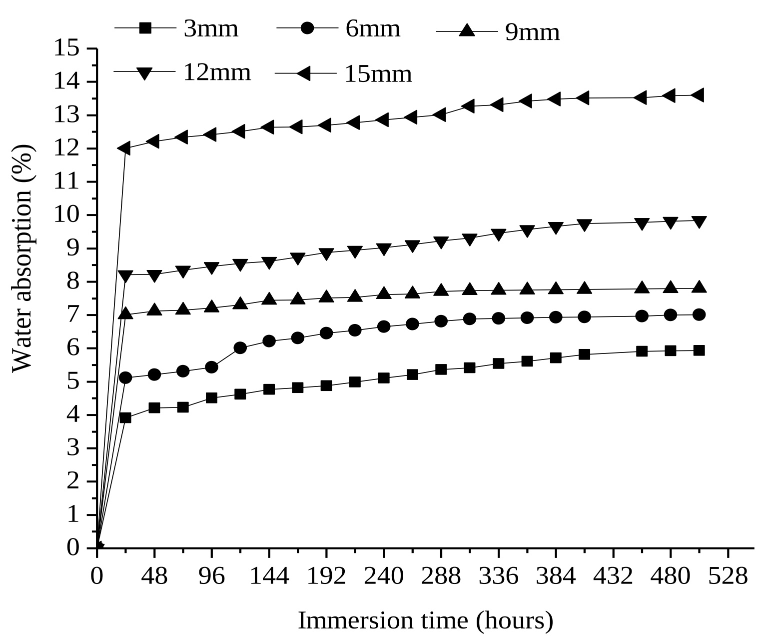

Figure 4.19: Water absorption behaviour of coir fiber reinforced epoxy composites with 20 wt% fiber content

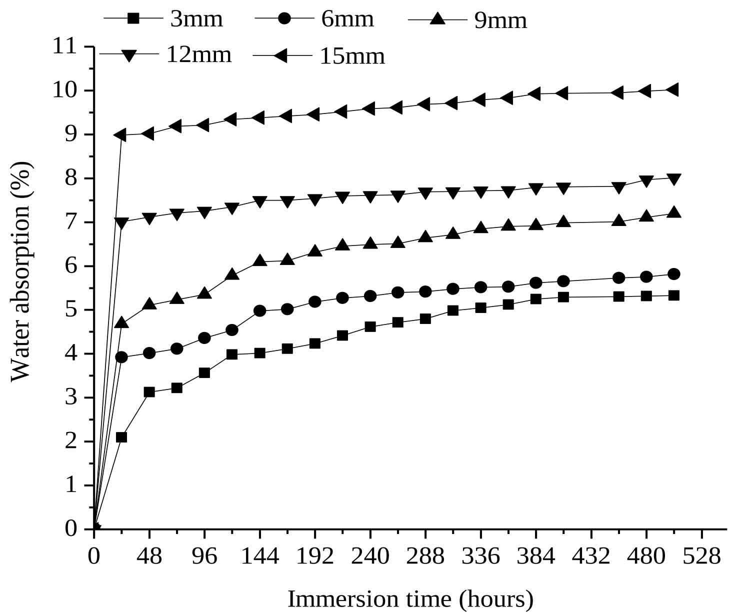

Figure 4.20: Water absorption behaviour of Al_2O_3 filled coir fiber reinforced epoxy composites with 5 wt% fiber content

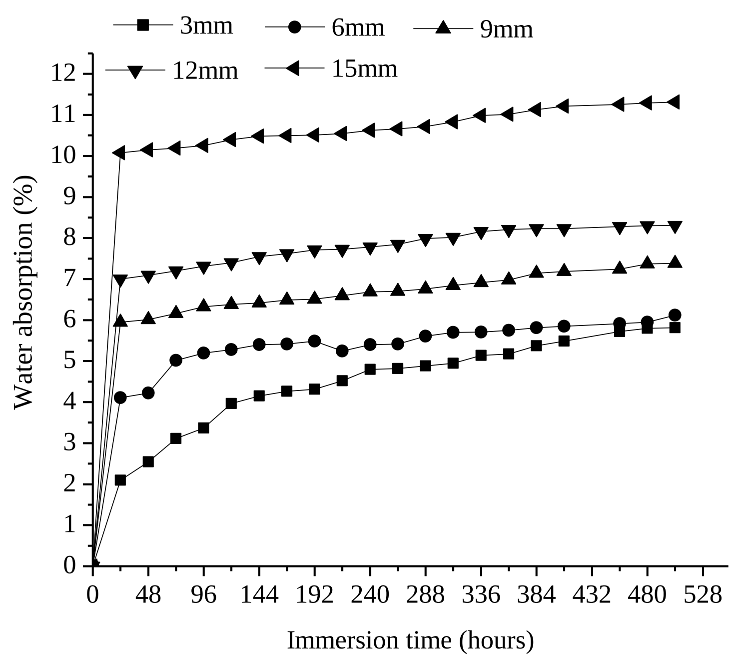

Figure 4.21: Water absorption behaviour of Al_2O_3 filled coir fiber reinforced epoxy composites with 10 wt% fiber content

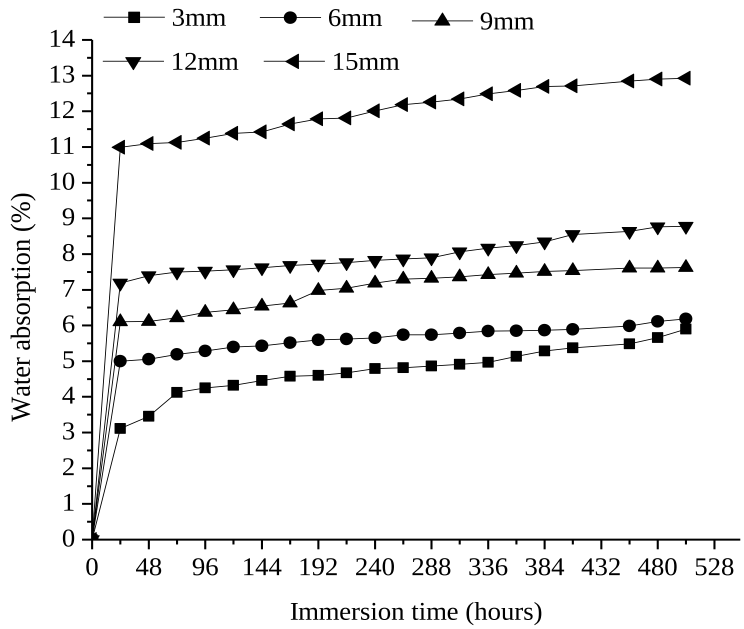

Figure 4.22: Water absorption behaviour of Al_2O_3 filled coir fiber reinforced epoxy composites with 15 wt% fiber content

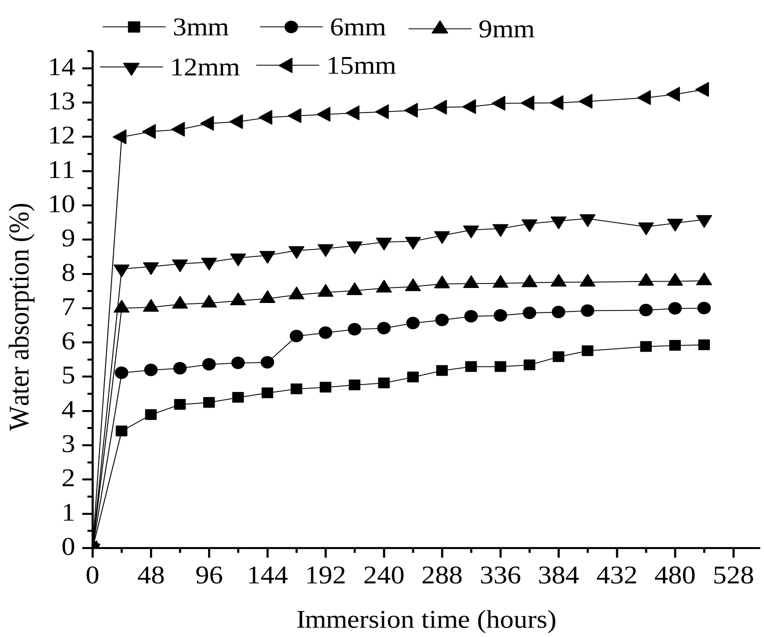

Figure 4.23: Water absorption behaviour of Al_2O_3 filled coir fiber reinforced epoxy composites with 20 wt% fiber content

4.3 Fractography

The fractographs of the composite samples which were obtained using SEM after tensile and flexural tests is shown in Figure 4.24. From the SEM photograph, pulled-out fibers are clearly visible for composites with 5 wt% fiber content and 3 mm length (Figures 4.24a and c after tensile and flexural tests respectively).

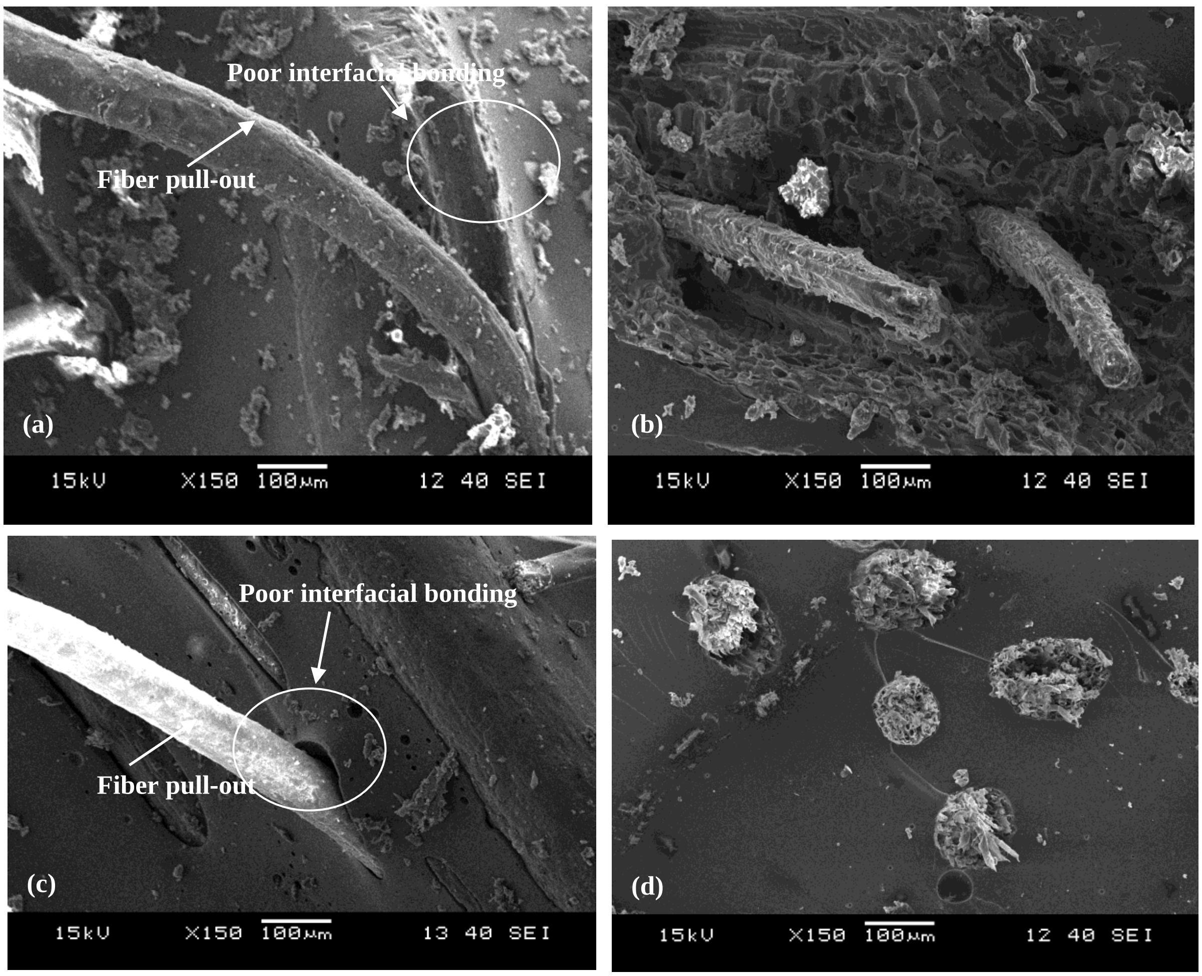

Figure 4.24: SEM micrographs of fractured surface of composites after tensile and flexural tests

It can be clearly seen from the figure that the fibers are detached from the resin surface due to the poor interfacial bonding. It can also be seen that the surfaces of the pulled out fibers are clean. As a comparison, the composite with 15 wt% fiber and 12 mm length shows good matrix/fiber adhesion. Only very small fiber pull-outs which were coated with matrix material is observed (Figures 4.24b and d after tensile and flexural tests respectively). The fracture surfaces study of Al_2O_3 filled composites after tensile test is shown in Figures 4.25a and b. From Figure 4.25a it is clear that the fibers are detached from the resin surface due to poor interfacial bonding. Pulled-out fibers are clearly visible for composites with 5 wt% fiber content and 3 mm length. However, the composite with 15 wt% fiber and 12 mm length shows good matrix/fiber adhesion. Only very small fiber pull-out which coated with matrix material is observed as shown in Figure 4.25b.

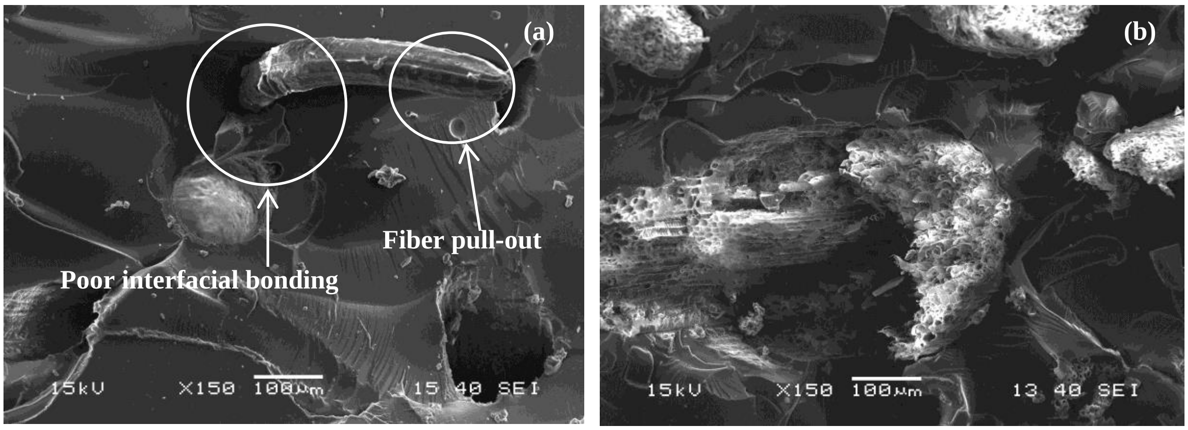

Figure 4.25: SEM micrographs of fractured surface of composites filled with Al_2O_3 filler after tensile tests

Chapter Summary

This chapter has provided:

- The physical, mechanical and water absorption behaviour of the coir fiber reinforced epoxy composites with and without filler and their comparison.
- The effects of fiber content, fiber length and filler on various properties of these composites

The next chapter presents the erosion wear behaviour of coir fiber reinforced epoxy composites with and without filler and their comparison.

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Chapter 5
Results and Discussion: Erosion Wear Behaviour of Composites

This chapter presents the erosion wear behaviour of the coir fiber reinforced epoxy composites with and without filler. The effect of impingement angle, impact velocity and fiber parameters on the erosion wear behaviour of composites is discussed.

5.1 Erosion Wear Behaviour of Composites

5.1.1 Steady state erosion

Influence of impingement angle on erosion wear behaviour

Generally, the erosion wear behaviour of materials can be grouped as ductile and brittle although this grouping is not definitive. Brittle behaviour is characterized by maximum erosion rate at normal impact (90°), and the ductile behaviour is characterized by the maximum erosion wear rate at 15-30° impingement angles. However, there is a dispute about this failure classification as the erosive wear behaviour depends strongly on the experimental conditions and the composition of the target material [183]. Steady-state erosion rates of coir fiber reinforced epoxy composites without filler as a function of impingement angle at impact velocity of 48 m/s are plotted in Figures 5.1a-d. It is observed from the figure that the erosion rate initially increases with the impingement angle, attains a peak value at 60° and then starts decreasing as the angle moves towards 90° for all composite samples irrespective of fiber length and fiber content. This clearly indicates that these composites respond to erosion neither in a purely ductile nor in a purely brittle manner. This behaviour can be termed as semi-ductile in nature. Figures 5.1a-d also demonstrates that erosion rate decreases with the increase in fiber content up to 15 wt% and then increases with further increase in fiber content. Similarly, fiber length also shows significant effect on erosion rate of composite materials. Composites with fiber length of 12 mm shows better wear resistance property as compared to others. A possible reason for the erosion behaviour is that the coir fiber used as reinforcement are typically brittle materials and the erosion is mainly caused by damage mechanisms such as micro-cracking due to the impact of silica sand particles. Such damage is supposed to increase with the increase of kinetic energy loss. The kinetic energy loss is maximum at normal impact (90°), where erosion rate is maximum for brittle materials [184].

Figures 5.2a-d show the effect of impingement angle on the erosion rate of coir fiber reinforced epoxy composites filled with Al_2O_3 filler at different fiber content and fiber length. It is observed from the figure that the peak erosion rate shifts to larger value of impingement angle (i.e. 75°). This clearly indicates that these composites with Al_2O_3 filler respond to solid particle impact in a semi-brittle manner which may be due to the brittle nature of Al_2O_3 filler and coir fiber incorporated into the epoxy matrix. The effect of fiber length and content on the erosion rate of composites with filler shows almost similar trend as the composites without filler. However, as far as comparison of composites with and without filler, Al_2O_3 filled coir epoxy composites shows better wear properties (i.e. less erosion rate) as compared to unfilled ones.

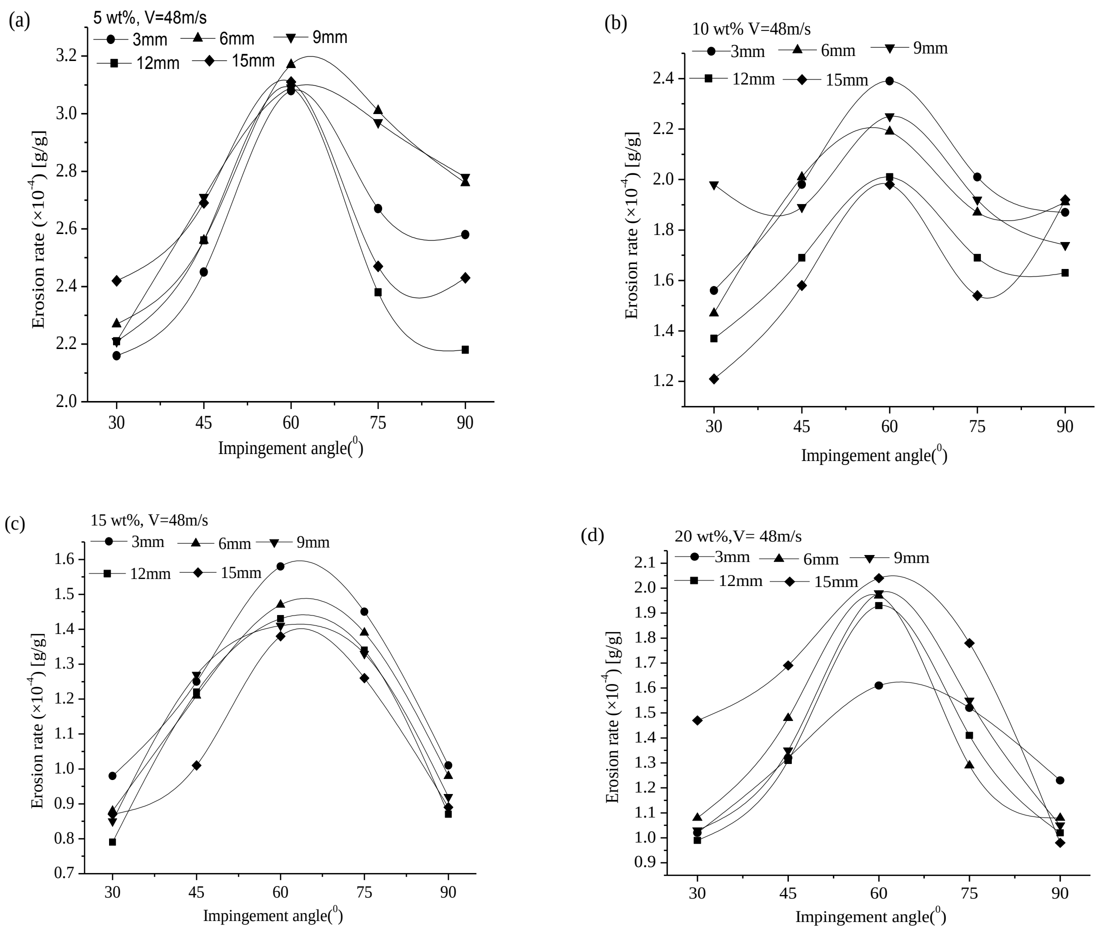

Figure 5.1: Effect of impingement angle on erosion rate of composites without filler at impact velocity of 48 m/s (a) at fiber content of 5 wt%, (b) at fiber content of 10 wt%, (c) at fiber content of 15 wt%, and (d) at fiber content of 20 wt%

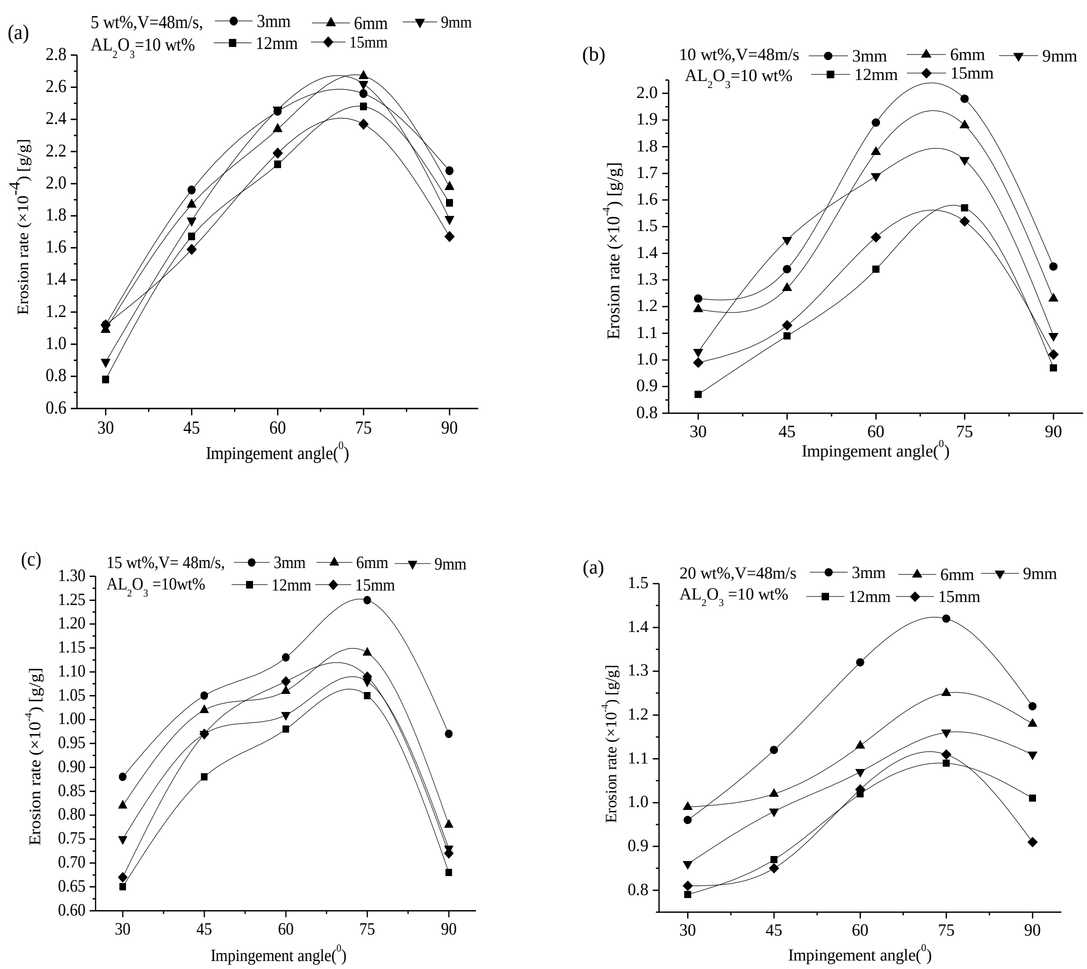

Figure 5.2: Effect of impingement angle on erosion rate of composites with Al_2O_3 filler at impact velocity of 48 m/s (a) at fiber content of 5 wt%, (b) at fiber content of 10 wt%, (c) at fiber content of 15 wt%, and (d) at fiber content of 20 wt%

Figures 5.3a-d and Figures 5.4a-d shows the erosion rate as a function of impingement angle at impact velocity of 70 m/s for composites with and without filler respectively. The variation of erosion rate with impingement angle for composites with and without filler at impact velocity of 82 m/s and 109 m/s shows the similar trend as shown in Figures 5.5-5.8. However, it is observed that as the impact velocity increases the erosion rate of composites increases irrespective of fiber content and length. The erosion rate reaches maximum at the impact velocity of 109 m/s for both Al_2O_3 filled and without filled composites. Similar observations were also reported by other investigators for some polymeric materials [185].

This may be due to the fact that with the increase in erodent particle velocity, the tangential component of the impact force which is cause for the erosion is increases.

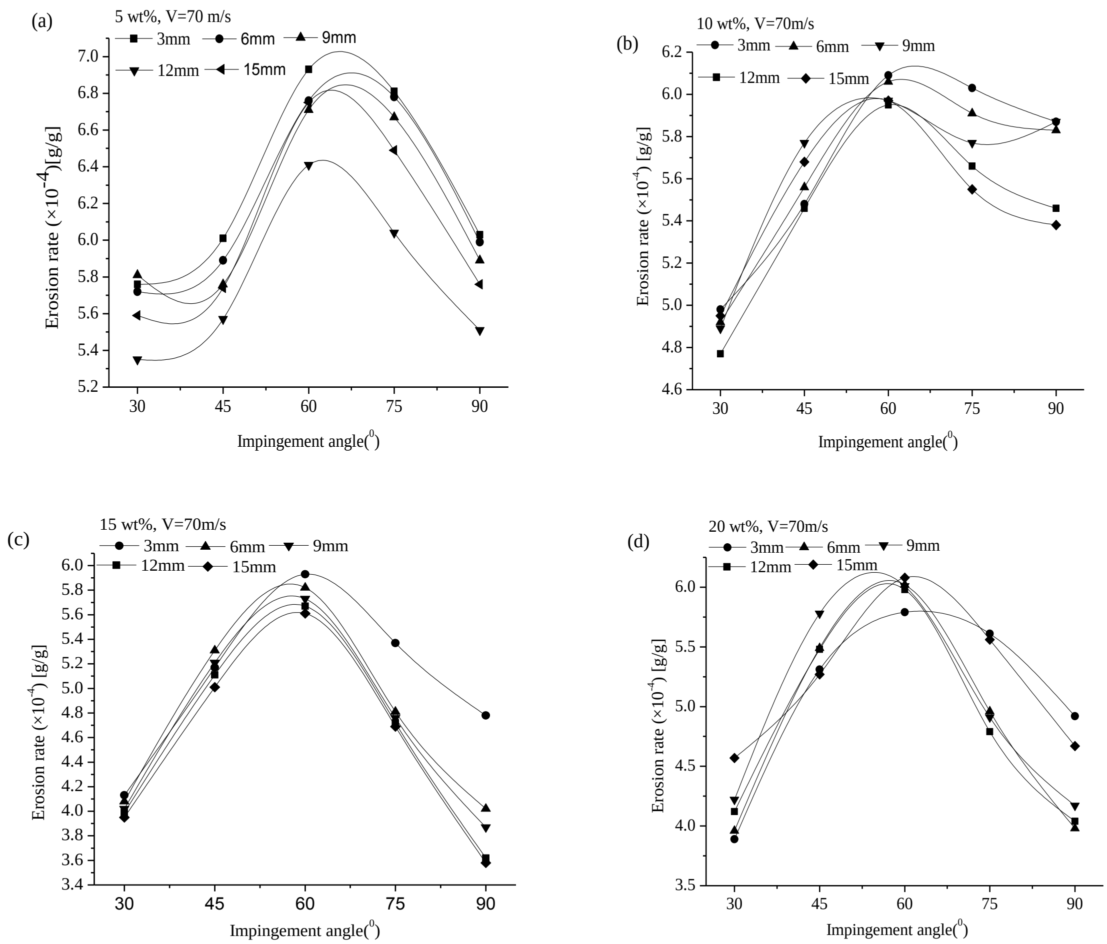

Figure 5.3: Effect of impingement angle on erosion rate of composites without filler at impact velocity of 70 m/s (a) at fiber content of 5 wt%, (b) at fiber content of 10 wt%, (c) at fiber content of 15 wt%, and (d) at fiber content of 20 wt%

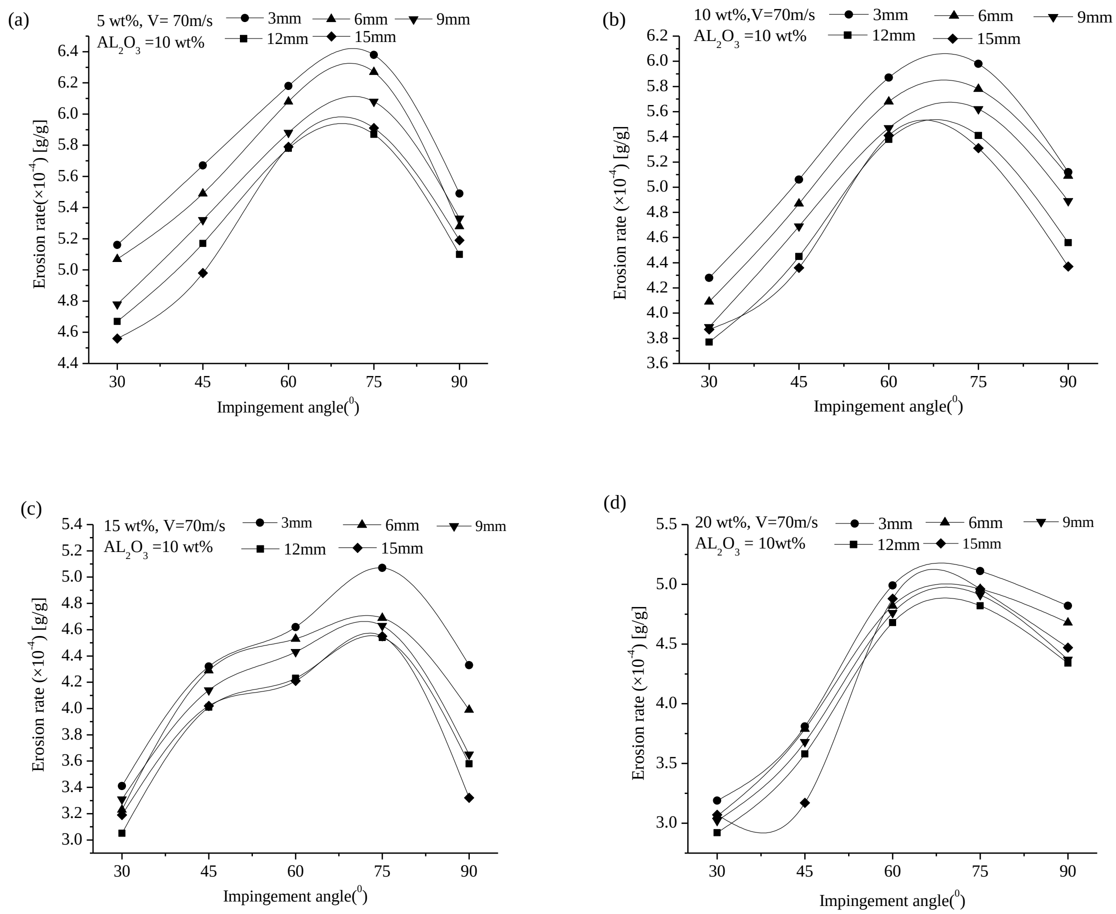

Figure 5.4: Effect of impingement angle on erosion rate of composites with Al_2O_3 filler at impact velocity of 70 m/s (a) at fiber content of 5 wt%, (b) at fiber content of 10 wt%, (c) at fiber content of 15 wt%, and (d) at fiber content of 20 wt%

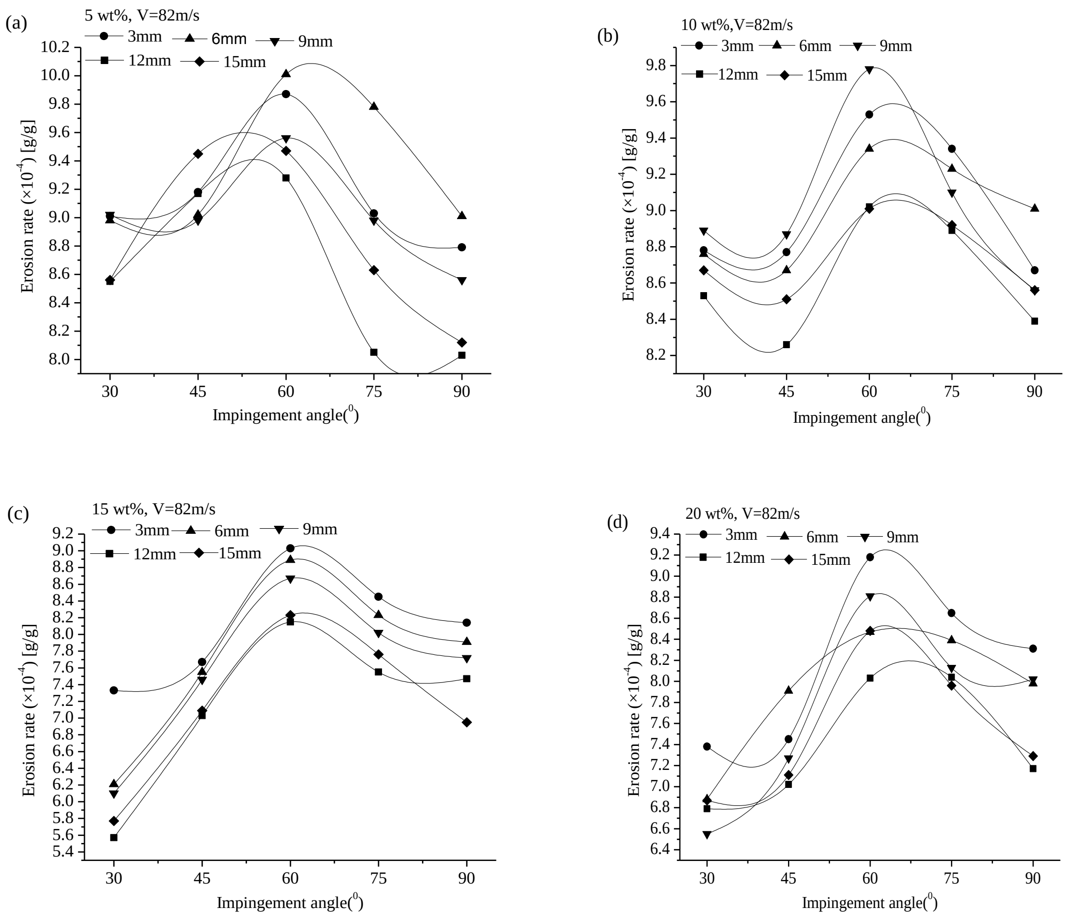

Figure 5.5: Effect of impingement angle on erosion rate of composites without filler at of 82 m/s (a) at fiber content of 5 wt%, (b) at fiber content of 10 wt%, (c) at fiber content of 15 wt%, and (d) at fiber content of 20 wt%

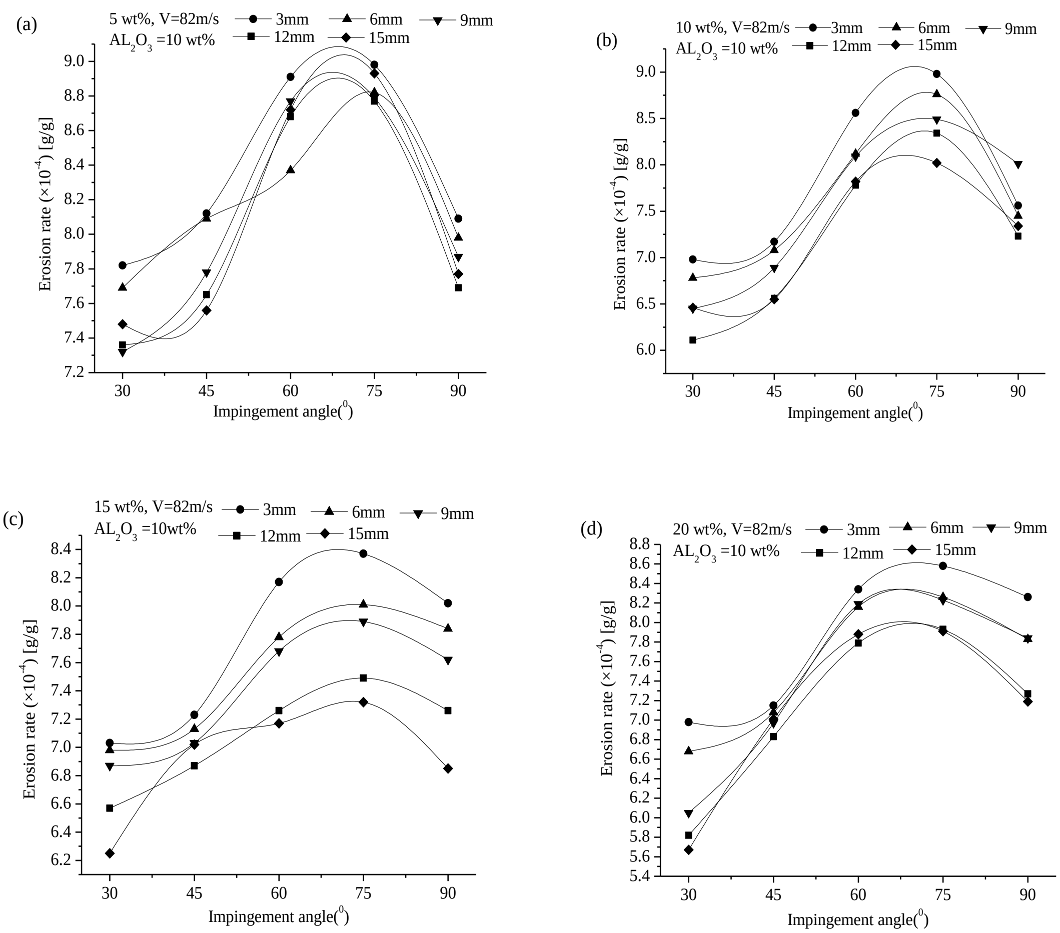

Figure 5.6: Effect of impingement angle on erosion rate of composites with Al_2O_3 filler at impact velocity of 82 m/s (a) at fiber content of 5 wt%, (b) at fiber content of 10 wt%, (c) at fiber content of 15 wt%, and (d) at fiber content of 20 wt%

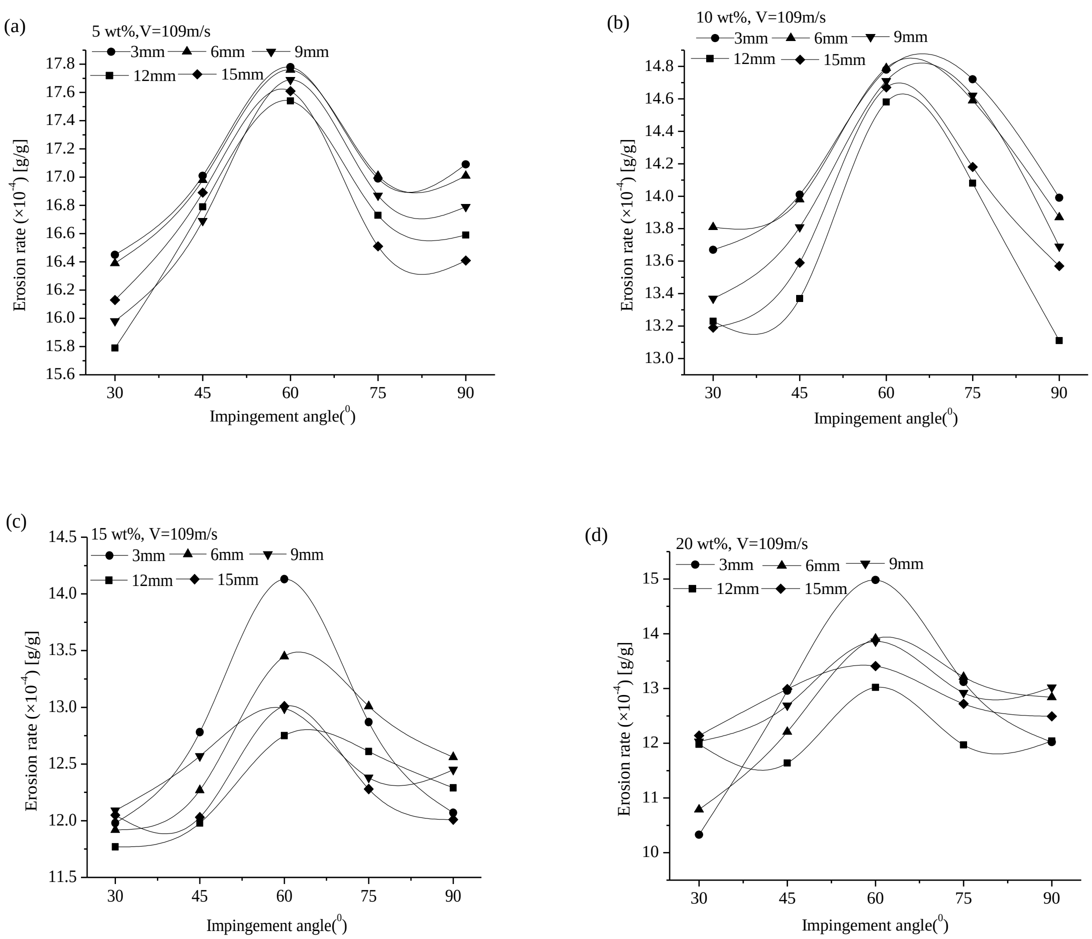

Figure 5.7: Effect of impingement angle on erosion rate of composites without filler at impact velocity of 109 m/s (a) at fiber content of 5 wt%, (b) at fiber content of 10 wt%, (c) at fiber content of 15 wt%, and (d) at fiber content of 20 wt%

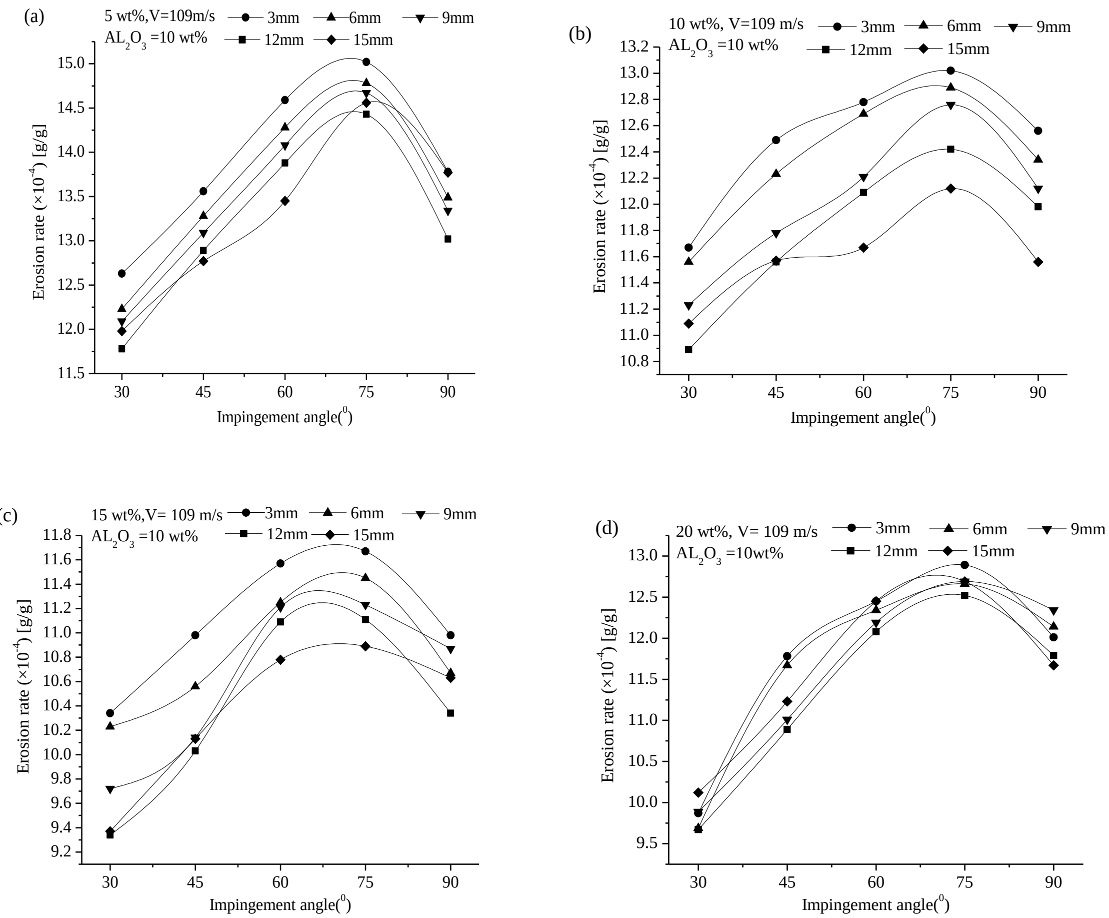

Figure 5.8: Effect of impingement angle on erosion rate of composites with Al_2O_3 filler impact velocity of 109 m/s (a) at fiber content of 5 wt%, (b) at fiber content of 10 wt%, (c) at fiber content of 15 wt%, and (d) at fiber content of 20 wt%

5.2 Surface Morphology

Microstructures of the un-eroded surfaces of unfilled and Al_2O_3 filled coir fiber reinforced epoxy composites are presented in Figures 5.9a and b respectively. Al_2O_3 particles are seen to be scattered on the upper surface and their distribution is reasonably uniform although at places the particles are seen to have formed small clusters (Figure 5.9b). SEM images of the eroded surfaces of the coir fiber reinforced epoxy composites are shown in Figures 5.10 and 5.11 eroded under various test conditions. The worn surfaces of the unfilled coir fiber reinforced epoxy composite are shown in Figures 5.10a-c. It is observed from Figure 5.10a that no cracks or craters are seen on the composite surface after erosion due to impact of dry silica sand particles at low impact velocity (48 m/s) and impingement angle (30°) with fiber content of 10 wt% at fiber length of 3 mm. But as the erosion tests were carried out with higher impact velocity (82 m/s) keeping other parameter constant, the morphology of the eroded surface became different as shown in Figure 5.10b. The matrix is chipped off and the coir fibers are clearly visible beneath the matrix layer. The fragmentation of the fibers as a result of cracks and multiple fractures are also distinctly observed in figure at impact velocity of 82 m/s. At higher impact velocity (109 m/s) and impingement angle 60° due to continuous exposure of fibers to erosion environment results in fiber thinning, detachment of fibers from the matrix and thus craters are formed (Figure 5.10c). This is the case of maximum material loss due to impact erosion.

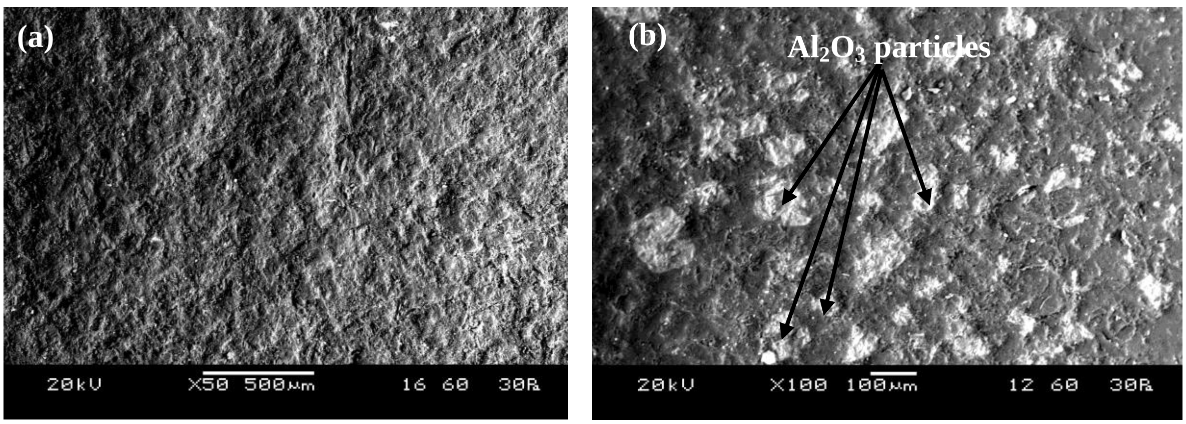

Figure 5.9: SEM of un-eroded surfaces of unfilled and Al_2O_3 filled coir fiber reinforced epoxy composites (48 m/s, 10 wt%, 30°)

Morphologies of the worn surfaces of Al_2O_3 filled coir fiber reinforced epoxy composites are shown in Figures 5.11a-c. It is observed from the Figure 5.11a that the damage to the surface of composite materials with 10 wt% of fiber content at low impact velocity (48 m/sec) and impingement angle (30°) is minimal. The fibers are still held firmly in place as yet by the matrix surrounding them. The removal of matrix material from the impact surface of the composite at lower impingement angle (30°) and impact velocity (82 m/sec) resulting in exposure of small amount of fibers to erosive environment can be clearly seen (Figure 5.11b). The fiber matrix debonding, brittle fracture of matrix and pulverization of fibers are also reflected in the micrograph. Figure 5.11c shows the SEM image of eroded surfaces of composite at higher impact velocity (109 m/s) and impingement angle 60°. When impact velocity increases to 109 m/s and impingement angle changes to 60°, the fibers are completely broken by means of shearing action and protruding of fibers from matrix can be seen from the micrograph. It is also clearly observed from the Figures 5.10 and 5.11 that the

Al_2O_3 filled coir fiber reinforced epoxy composites shows less damage as compared to unfilled composites irrespective of impact velocity and impingement angle.

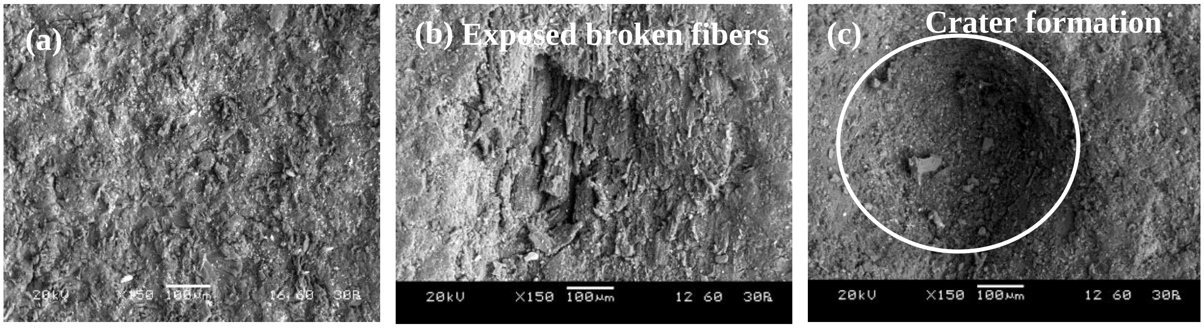

Figure 5.10: SEM of surfaces of the unfilled coir fiber reinforced epoxy composite (10 wt%, 3 mm, 30°)

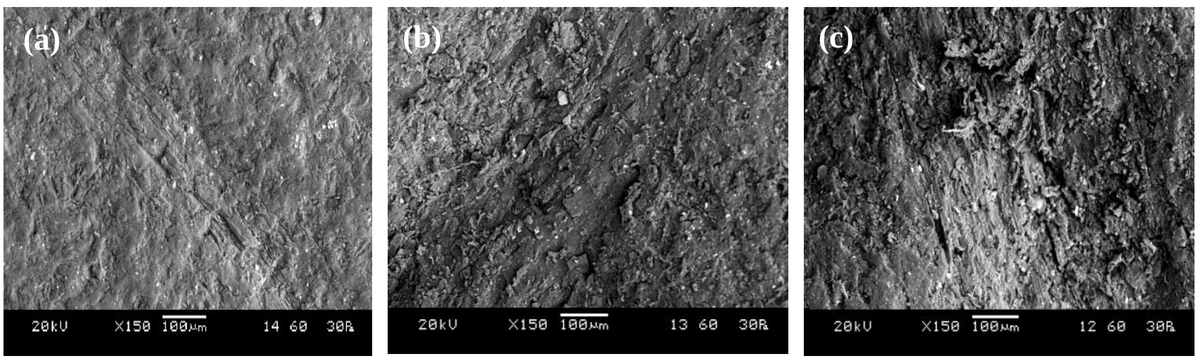

Figure 5.11: SEM of surfaces of the Al_2O_3 filled coir fiber reinforced epoxy composite (10 wt%, 3 mm, 30°)

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Chapter 6
Ranking of the Materials

Materials selection is defined as a factor that effects on the selection of a material for a given application and is generally carried out by designers and materials engineers. It can be noted that there is not always a single definite criterion of selection for choosing the right material. Therefore, designers and engineers have to take into account a large number of materials selection criteria. Decision-making is the study of identifying and choosing the alternatives to find the best solution based on the different parameters and considering the decision-makers' expectations. In almost all such problems the multiplicity of criteria for judging the alternatives is pervasive. These criteria usually conflict with each other so there may be no solution satisfying all criteria simultaneously. In the present research work, a MCDM technique called TOPSIS is used for ranking the materials and to select the best alternative from the fabricated composite materials based on their physical, mechanical, water absorption and erosion wear properties.

A step-by-step procedure is followed for the process of material selection. It consists of constructing the normalized matrix from the database matrix, the weighted normalized matrix, and obtaining the positive and negative benchmarking values. The materials are ranked by obtaining the indices showing closeness to the positive benchmarking values. The higher the index, the better is the rank of the material. The objective is to evaluate the forty alternatives, and the attributes are: tensile strength, tensile modulus, flexural strength, micro-hardness, density, impact strength, water absorption and erosion wear rate. For this particular problem, tensile strength, tensile modulus, flexural strength, micro-hardness and impact strength are considered as beneficial attribute (i.e. higher values); while density, water absorption and erosion wear rate are considered as non-beneficial (i.e. smaller values). The decision matrix, normalized decision matrix, weight normalized decision matrix, ideal positive and ideal negative solution and separation measure values are calculated and presented in Table 6.1, Table 6.2, Table 6.3, Table 6.4 and Table 6.5, respectively. Finally, the rank is given to alternatives according to the relative closeness to ideal solution as shown in Table 6.6. The ranking of composite materials are as follows: 1(S14), 2(S18), 3(S17), 4(S13), 5(S12), 6(S19), 7(S11), 8(S9), 9(C14), 10(S16), 11(C13), 12(S8), 13(S15), 14(C12), 15(C19), 16(C17), 17(C18), 18(S20), 19(C11), 20(S7), 21(C9), 22(S10), 23(C16), 24(C8), 25(S6), 26(S4), 27(S3), 28(C15), 29(C20), 30(C7), 31(S2), 32(C10), 33(S1), 34(S5), 35(C6), 36(C3), 37(C4), 38(C2), 39(C1), 40(C5). It is observed from the Table 6.6 that the material designated as S14 i.e. composite with 10 wt% Al_2O_3 filler, 15 wt% fiber content and 12 mm fiber length shows best alternative material. As per the ranking order, S14 is the first choice, S18 is the second choice and C5 is the last choice among all the composite materials under the present study based on their physical, mechanical, water absorption and erosion wear properties. As can be seen from obtained results, the TOPSIS method considers all the attributes along with their relative importance, and hence, it can provide a better accurate evaluation of the alternatives. This method is computationally very simple, easily comprehendible, and robust which can simultaneously consider any number of qualitative and quantitative selection attributes, while offering a more objective and logical selection approach. The suggested methodology can also be used for any type of selection problem involving any number of selection criteria.

Table 6.1: Decision matrix

Composites materials	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Micro-hardness (Hv)	Density (gm/cc^3)	Impact strength (kJ/m^2)	Water absorption (wt%)	Erosion rate (g/g)
C1	16.18	1.274	11.37	9.25	1.0951	10.26	4.6364	8.784
C2	18.02	1.692	12.99	9.86	1.0881	11.16	5.2574	8.843
C3	19.48	1.882	16.47	11.73	1.0799	11.81	6.5137	8.686
C4	20.39	1.999	18.71	13.1	1.0672	12.16	7.7223	9.2305
C5	20.62	2.081	16.01	14.29	1.0548	11.98	9.6823	8.5615
C6	19.55	1.317	14.79	10.35	1.0971	11.01	4.7952	7.726
C7	20.27	1.707	18.36	10.87	1.0891	11.98	5.8182	7.689
C8	22.57	1.929	23.24	12.35	1.0816	12.43	6.7733	7.6725
C9	23.1	2.036	25.18	14.55	1.0681	12.71	7.8652	7.3325
C10	22.92	2.155	23.23	15.27	1.0551	12.18	10.8223	7.4315
C11	21.75	1.443	25.29	13.75	1.0991	12.38	4.9956	6.805
C12	22.17	1.748	27.81	14.17	1.0912	12.71	5.6822	6.5985
C13	23.34	1.941	28.79	14.95	1.0832	13.15	7.0758	6.491
C14	24.74	2.114	29.43	16.34	1.0692	13.54	7.7425	6.2815
C15	24.11	2.203	27.14	17.43	1.0561	13.18	12.1896	6.2715
C16	20.35	1.621	19.03	15.4	1.1001	11.32	5.1256	6.83
C17	21.37	1.831	22.83	17.13	1.0923	11.67	5.7859	6.695
C18	22.65	1.96	25.19	17.86	1.0851	11.94	7.5428	6.7675
C19	23.86	2.197	27.54	18.25	1.0701	12.08	9.0755	6.4385
C20	22.95	2.269	25.65	18.61	1.0582	12.32	12.9377	6.7785
S1	17.19	1.612	12.12	9.72	1.1931	11.01	4.4263	7.5275
S2	19.11	1.841	13.33	10.11	1.1923	12.33	5.1308	7.3575
S3	21.22	2.031	17.21	12.22	1.1783	12.78	6.3248	7.2355
S4	22.36	2.124	19.23	13.34	1.1682	13.21	7.5765	7.0835
S5	21.24	2.331	17.13	14.52	1.1591	12.64	9.5775	7.118
S6	20.23	2.015	15.34	11.03	1.1949	12.12	4.682	6.7935
S7	22.48	2.117	18.61	11.45	1.1938	13.07	5.4268	6.638
S8	24.61	2.212	23.56	13.21	1.1792	13.53	6.7019	6.48
S9	25.14	2.484	25.75	14.87	1.1691	14.43	7.7968	6.2185
S10	24.46	2.645	23.46	15.45	1.1602	13.82	10.7064	6.182
S11	22.57	2.142	25.61	14.23	1.1959	13.14	4.7375	6.0695
S12	24.35	2.364	28.07	15.06	1.1951	14.26	5.6366	5.8725
S13	25.53	2.571	29.22	15.51	1.1805	14.52	7.0198	5.748
S14	25.71	3.013	29.75	17.21	1.1705	14.76	7.953	5.5505
S15	25.34	3.261	27.92	18.32	1.1611	14.28	12.0229	5.5115
S16	21.51	2.331	20.06	15.35	1.1972	12.32	4.9354	6.3135
S17	23.42	2.721	23.13	17.56	1.1961	12.72	6.2665	6.1695
S18	23.83	2.911	25.65	18.11	1.1814	12.93	7.5055	6.066
S19	24.44	3.172	27.78	19.25	1.1721	13.05	8.9451	5.8855
S20	23.52	3.412	25.82	19.52	1.1625	12.66	12.7339	5.954

Table 6.2: Normalized decision matrix

Composites materials	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Micro-hardness (Hv)	Density (gm/cc^3)	Impact strength (kJ/m^2)	Water absorption (wt%)	Erosion rate (g/g)
C1	0.114552369	0.090605605	0.078734367	0.098722702	0.153128669	0.127950448	0.094856519	0.199695118
C2	0.127579338	0.120333347	0.089952456	0.105233064	0.152149853	0.139174171	0.107561613	0.201036422
C3	0.137915955	0.133845957	0.114050574	0.125191059	0.151003241	0.147280194	0.133264366	0.19746719
C4	0.144358641	0.14216688	0.129562006	0.139812692	0.14922739	0.151644975	0.157991221	0.209845832
C5	0.145987012	0.147998637	0.110865191	0.152513234	0.147493489	0.14940023	0.198091035	0.194636812
C6	0.138411546	0.093663722	0.102417	0.110462699	0.15340833	0.137303551	0.098105422	0.175642587
C7	0.143509056	0.121400132	0.127138345	0.116012516	0.152289684	0.14940023	0.11903507	0.17480143
C8	0.159792767	0.13718855	0.160931108	0.131808148	0.151240953	0.155012092	0.138575546	0.17442632
C9	0.1635451	0.144798282	0.174365116	0.155288142	0.149353238	0.158503917	0.160914824	0.166696773
C10	0.162270723	0.153261443	0.16086186	0.162972504	0.147535438	0.151894391	0.221414396	0.168947435
C11	0.15398727	0.102624716	0.175126838	0.146749963	0.153687992	0.154388552	0.102205424	0.154704608
C12	0.156960817	0.124316011	0.192577199	0.151232507	0.152583329	0.158503917	0.116252634	0.150010045
C13	0.16524427	0.138041978	0.19936345	0.159557232	0.151464682	0.163991071	0.14476442	0.147566144
C14	0.175156095	0.150345564	0.203795288	0.174392319	0.149507052	0.168854685	0.158404494	0.142803379
C15	0.170695774	0.156675155	0.187937619	0.186025589	0.147675269	0.164365195	0.249388108	0.14257604
C16	0.144075446	0.115283898	0.131777925	0.164359958	0.153827822	0.1411695	0.104865105	0.155272957
C17	0.151296918	0.130218888	0.158091961	0.182823772	0.152737142	0.145534281	0.118374241	0.152203873
C18	0.160359157	0.139393239	0.174434363	0.190614861	0.151730361	0.148901398	0.154318814	0.153852085
C19	0.168925805	0.156248441	0.190707517	0.194777223	0.149632899	0.150647311	0.18567646	0.146372611
C20	0.162483119	0.161369009	0.177619746	0.198619404	0.147968913	0.153640304	0.264693552	0.154102158
S1	0.121703042	0.114643827	0.083927927	0.103738883	0.166832083	0.137303551	0.090558064	0.171129896
S2	0.135296401	0.130930078	0.09230687	0.107901245	0.166720219	0.153765012	0.104971492	0.167265122
S3	0.150234936	0.144442688	0.119174886	0.130420694	0.164762588	0.159376874	0.129399644	0.164491579
S4	0.158305993	0.151056754	0.133162874	0.142374146	0.163350297	0.164739319	0.155008286	0.161036017
S5	0.150376534	0.165778387	0.118620907	0.154967961	0.162077837	0.157630961	0.195946922	0.161820338
S6	0.143225861	0.143304784	0.106225611	0.117720152	0.167083779	0.151146143	0.095789453	0.154443168
S7	0.159155578	0.150558921	0.128869531	0.122202696	0.166929965	0.162993407	0.111027383	0.150908037
S8	0.174235711	0.157315226	0.163147026	0.140986691	0.164888436	0.168729976	0.137114767	0.147316071
S9	0.177988044	0.176659594	0.178312221	0.158703414	0.163476145	0.1799537	0.159515423	0.14137114
S10	0.17317373	0.188109753	0.162454552	0.164893594	0.162231651	0.17234651	0.219043187	0.14054135
S11	0.159792767	0.152336896	0.177342757	0.15187287	0.167223609	0.163866363	0.096924933	0.13798378
S12	0.172394943	0.168125314	0.194377633	0.160731232	0.167111745	0.177833663	0.115319699	0.133505189
S13	0.180749195	0.182846947	0.202341091	0.165533958	0.165070216	0.181076072	0.143618711	0.130674811
S14	0.182023573	0.214281545	0.206011207	0.18367759	0.163671908	0.184069065	0.162711132	0.126184854
S15	0.179404019	0.231919057	0.193338921	0.195524314	0.162357499	0.178083079	0.245977578	0.125298229
S16	0.1522881	0.165778387	0.138910414	0.163826322	0.167405389	0.153640304	0.100973786	0.143530866
S17	0.16581066	0.193514797	0.160169385	0.187413043	0.167251576	0.158628625	0.128206879	0.140257176
S18	0.168713409	0.207027407	0.177619746	0.193283042	0.165196063	0.161247494	0.15355569	0.137904211
S19	0.173032132	0.225589466	0.192369456	0.205449948	0.163895637	0.162743991	0.183008594	0.133800731
S20	0.166518648	0.242658025	0.178796953	0.208331583	0.162553262	0.157880377	0.26052399	0.135358007

Table 6.3: Weighted normalized decision matrix

Composites materials	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Micro-hardness (Hv)	Density (gm/cc^3)	Impact strength (kJ/m^2)	Water absorption (wt%)	Erosion rate (g/g)
C1	0.014319046	0.011325701	0.009841796	0.012340338	0.019141084	0.015993806	0.011857065	0.02496189
C2	0.015947417	0.015041668	0.011244057	0.013154133	0.019018732	0.017396771	0.013445202	0.025129553
C3	0.017239494	0.016730745	0.014256322	0.015648882	0.018875405	0.018410024	0.016658046	0.024683399
C4	0.01804483	0.01777086	0.016195251	0.017476586	0.018653424	0.018955622	0.019748903	0.026230729
C5	0.018248376	0.01849983	0.013858149	0.019064154	0.018436686	0.018675029	0.024761379	0.024329601
C6	0.017301443	0.011707965	0.012802125	0.013807837	0.019176041	0.017162944	0.012263178	0.021955323
C7	0.017938632	0.015175016	0.015892293	0.014501564	0.01903621	0.018675029	0.014879384	0.021850179
C8	0.019974096	0.017148569	0.020116388	0.016476019	0.018905119	0.019376512	0.017321943	0.02180329
C9	0.020443138	0.018099785	0.021795639	0.019411018	0.018669155	0.01981299	0.020114353	0.020837097
C10	0.02028384	0.01915768	0.020107733	0.020371563	0.01844193	0.018986799	0.027676799	0.021118429
C11	0.019248409	0.012828089	0.021890855	0.018343745	0.019210999	0.019298569	0.012775678	0.019338076
C12	0.019620102	0.015539501	0.02407215	0.018904063	0.019072916	0.01981299	0.014531579	0.018751256
C13	0.020655534	0.017255247	0.024920431	0.019944654	0.018933085	0.020498884	0.018095552	0.018445768
C14	0.021894512	0.018793196	0.025474411	0.02179904	0.018688381	0.021106836	0.019800562	0.017850422
C15	0.021336972	0.019584394	0.023492202	0.023253199	0.018459409	0.020545649	0.031173513	0.017822005
C16	0.018009431	0.014410487	0.016472241	0.020544995	0.019228478	0.017646187	0.013108138	0.01940912
C17	0.018912115	0.016277361	0.019761495	0.022852971	0.019092143	0.018191785	0.01479678	0.019025484
C18	0.020044895	0.017424155	0.021804295	0.023826858	0.018966295	0.018612675	0.019289852	0.019231511
C19	0.021115726	0.019531055	0.02383844	0.024347153	0.018704112	0.018830914	0.023209557	0.018296576
C20	0.02031039	0.020171126	0.022202468	0.024827426	0.018496114	0.019205038	0.033086694	0.01926277
S1	0.01521288	0.014330478	0.010490991	0.01296736	0.02085401	0.017162944	0.011319758	0.021391237
S2	0.01691205	0.01636626	0.011538359	0.013487656	0.020840027	0.019220626	0.013121437	0.02090814
S3	0.018779367	0.018055336	0.014896861	0.016302587	0.020595324	0.019922109	0.016174956	0.020561447
S4	0.019788249	0.018882094	0.016645359	0.017796768	0.020418787	0.020592415	0.019376036	0.020129502
S5	0.018797067	0.020722298	0.014827613	0.019370995	0.02025973	0.01970387	0.024493365	0.020227542
S6	0.017903233	0.017913098	0.013278201	0.014715019	0.020885472	0.018893268	0.011973682	0.019305396
S7	0.019894447	0.018819865	0.016108691	0.015275337	0.020866246	0.020374176	0.013878423	0.018863505
S8	0.021779464	0.019664403	0.020393378	0.017623336	0.020611054	0.021091247	0.017139346	0.018414509
S9	0.022248506	0.022082449	0.022289028	0.019837927	0.020434518	0.022494212	0.019939428	0.017671392
S10	0.021646716	0.023513719	0.020306819	0.020611699	0.020278956	0.021543314	0.027380398	0.017567669
S11	0.019974096	0.019042112	0.022167845	0.018984109	0.020902951	0.020483295	0.012115617	0.017247972
S12	0.021549368	0.021015664	0.024297204	0.020091404	0.020888968	0.022229208	0.014414962	0.016688149
S13	0.022593649	0.022855868	0.025292636	0.020691745	0.020633777	0.022634509	0.017952339	0.016334351
S14	0.022752947	0.026785193	0.025751401	0.022959699	0.020458989	0.023008633	0.020338892	0.015773107
S15	0.022425502	0.028989882	0.024167365	0.024440539	0.020294687	0.022260385	0.030747197	0.015662279
S16	0.019036012	0.020722298	0.017363802	0.02047829	0.020925674	0.019205038	0.012621723	0.017941358
S17	0.020726333	0.02418935	0.020021173	0.02342663	0.020906447	0.019828578	0.01602586	0.017532147
S18	0.021089176	0.025878426	0.022202468	0.02416038	0.020649508	0.020155937	0.019194461	0.017238026
S19	0.021629017	0.028198683	0.024046182	0.025681243	0.020486955	0.020342999	0.022876074	0.016725091
S20	0.020814831	0.030332253	0.022349619	0.026041448	0.020319158	0.019735047	0.032565499	0.016919751

Table 6.4: Positive and negative ideal solution matrix

	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Micro-hardness (Hv)	Density (gm/cc^3)	Impact strength (kJ/m^2)	Water absorption (wt%)	Erosion rate (g/g)
Positive Ideal Solution	0.022752947	0.030332253	0.025751401	0.026041448	0.018436686	0.023008633	0.011319758	0.015662279
Negative Ideal Solution	0.014319046	0.011325701	0.009841796	0.012340338	0.020925674	0.015993806	0.033086694	0.026230729

Table 6.5: Separation Measure

Composites	S+	S-
C1	0.031775637	0.021342255
C2	0.027975734	0.020290248
C3	0.02422311	0.018722031
C4	0.023320556	0.017720077
C5	0.025000185	0.014647789
C6	0.027733358	0.02182393
C7	0.023524263	0.020752167
C8	0.019797281	0.021730426
C9	0.018137502	0.022211091
C10	0.02254914	0.018366771
C11	0.020562862	0.026109081
C12	0.017688326	0.026640129
C13	0.016537022	0.025886436
C14	0.015243153	0.026923898
C15	0.023136607	0.02289214
C16	0.02095083	0.024201279
C17	0.017474834	0.02547863
C18	0.017038291	0.024393802
C19	0.017079465	0.025041674
C20	0.024990343	0.022082087
S1	0.028099071	0.022566224
S2	0.025291569	0.021764345
S3	0.020998563	0.02097913
S4	0.019632036	0.020240643
S5	0.021919279	0.017513676
S6	0.022321661	0.023996171
S7	0.019473952	0.024032492
S8	0.016253317	0.024615683
S9	0.014190724	0.026044976
S10	0.019337983	0.02278158
S11	0.014609751	0.028778912
S12	0.011959056	0.029896267
S13	0.01158281	0.029682645
S14	0.010369454	0.031580166
S15	0.019708341	0.029769251
S16	0.015330332	0.027040587
S17	0.011107271	0.02853937
S18	0.010782692	0.029006526
S19	0.012443475	0.030522114
S20	0.021967048	0.029136593

Table 6.6: Relative closeness value and ranking

Composites	Closeness factor	Rank
C1	0.401790328	39th
C2	0.42038403	38th
C3	0.435952255	36th
C4	0.431769103	37th
C5	0.369446092	40th
C6	0.440377816	35th
C7	0.468695579	30th
C8	0.523275362	24th
C9	0.550479942	21st
C10	0.448890674	32th
C11	0.559417056	19th
C12	0.600971297	14th
C13	0.610191558	11th
C14	0.638505598	9th
C15	0.497344407	28th
C16	0.53599444	23rd
C17	0.593168224	16th
C18	0.588765867	17th
C19	0.594515594	15th
C20	0.469108707	29th
S1	0.445398054	33th
S2	0.462520932	31st
S3	0.499768539	27th
S4	0.507631882	26th
S5	0.444138054	34th
S6	0.518076298	25th
S7	0.55238924	20th
S8	0.602306957	12th
S9	0.647310128	8th
S10	0.540878825	22nd
S11	0.66328184	7th
S12	0.714276335	5th
S13	0.719309778	4th
S14	0.752811731	1st
S15	0.60167138	13th
S16	0.638187409	10th
S17	0.719843318	3rd
S18	0.729004682	2nd
S19	0.710385083	6th
S20	0.570147099	18th

Chapter Summary

This chapter has provided

- Ranking of the materials.

The next chapter refers to the conclusions of the present study, recommendations for the potential applications and scope for future research.

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Chapter 7
Conclusions

Based on the physical, mechanical, water absorption and erosion wear studies of coir fiber reinforced epoxy composites filled with Al_2O_3 filler; the following conclusions may be drawn:

- Fabrication of coir fiber reinforced epoxy composites with and without filler has been done successfully.
- It has been noticed that the properties of the coir fiber reinforced epoxy composites are significantly influenced by the fiber length and fiber content. The void content of the composites increases with the increase in both fiber content and fiber length.
- The strength properties of composite increases with increase in the fiber content up to 15 wt% and then decreases. Therefore, the optimum fiber content is found to be 15 wt% for better mechanical properties. Similarly, 12 mm fiber length is found to be effective in increasing the strength properties of composites. However, the tensile modulus and hardness of composites increases with increase in both fiber content and fiber length. Maximum tensile modulus and hardness is obtained for composites with 15 mm fiber length and 20 wt% fiber content.
- The water absorption behaviour of composites significantly influenced by the fiber parameters, filler and immersion time. The minimum water absorption is observed for composites with 5 wt% fiber content at 3 mm fiber length and the maximum water absorption is obtained for composites with 20 wt% fiber content at 15 mm fiber length.
- The improvement in mechanical properties of composites with Al_2O_3 filler is observed as compared to unfilled one. The rate of water absorption is less in case of Al_2O_3 filled composites as compared to unfilled one. Al_2O_3 filled composites with 5 wt% fiber content and 3 mm fiber length shows minimum water absorption rate as compared to all other types of composites under the present study.
- The erosive wear performance of coir fiber reinforced epoxy composites is dependent to a greater extent on the experimental parameters such as impingement angle and impact velocity. The influence of impingement angle on erosive wear of coir fiber reinforced epoxy composites without filler exhibited semi-ductile erosive wear behaviour as the peak erosion rate is found to be occurring at 60° impingement angle. However, the composites with Al_2O_3 filler respond to solid particle impact in a semi-brittle manner as

the peak erosion is found to be occurring at an impingement angle of 75°. The reason may be due to the brittle nature of Al_2O_3 filler and coir fiber incorporated into the epoxy matrix. Impact velocity has significant effect on the erosion wear behaviour of coir fiber reinforced epoxy composites. It is observed that increase in impact velocity increases the wear rate of composites irrespective of other parameters. The minimum and maximum wear rate is observed at impact velocity of 48 m/s and 109 m/s respectively.

- Fiber length and fiber content has significant effect on the erosion wear behaviour of composites. Composites with fiber length of 12 mm shows better wear resistance property as compared to others.
- The filler has also a significant influence of the erosion behaviour of composites. It is also observed that coir fiber reinforced epoxy composites filled with Al_2O_3 filler shows better wear resistance properties as compared to unfilled one irrespective of fiber content and length.
- The SEM studies of worn surfaces have revealed various wear mechanisms such as micro-ploughing, craters and micro cracking, fiber matrix de-bonding, fiber thinning, pulverization of fibers and brittle fracture of matrix.
- TOPSIS method is used for ranking the fabricated composites based on various properties. It is observed that the Al_2O_3 filled composites with 15 wt% fiber content and 12 mm fiber length shows the best alternative among all the composite materials under study.

7.1 Recommendation for Potential Application

The coir fiber reinforced epoxy composites fabricated and experimented upon in this investigation are found to have adequate potential for a wide range of applications particularly in hostile environment. These composites can be used for engineering structures in dusty environment and low cost building materials in deserts. Use of these composites, in general, may also be recommended for applications like partition boards, pipe lines carrying coal dust, false ceilings, exhaust fan blades, light weight vehicles, nozzles and diffusers etc.

7.2 Scope for Future Research

The present investigation on coir fiber reinforced epoxy composites leaves a wide scope for future researchers to find many other aspects of these composites. Few recommendations for the future investigation comprise:

- The present study has been carried out using simple hand lay-up technique. However, the research work can be extended further by considering other methods of composite fabrication and the effect of manufacturing techniques on the performance of composites can similarly be analyzed.
- Besides many advantages of natural fibers, the main disadvantages of natural fibers in composites are the poor compatibility between fiber and matrix and the relative high moisture absorption due to their hydrophilic nature. The limited compatibility between the constituents of a composite usually results in a decrease in the mechanical and wear properties. Therefore, the study can be extended further by considering the chemical treatments in modifying the fiber surface properties to improve the adhesion between fiber and matrix materials and the study can be analyzed similarly.
- The present study can be extended further by the development of composites using other particulate fillers along and the study can similarly be analyzed.
- Study on the response of these composites to other wear modes such as sliding and abrasion.
- Cost analysis of these composites to assess their economic viability in industrial applications.

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Dissemination

Journal Articles

1. Geetanjali Das and Sandhayarani Biswas, Effect of fiber parameters on physical, mechanical and water absorption behaviour of coir fiber/epoxy composites, Journal of Reinforced Plastics and Composites, 2016, doi:10.1177/0731684415626594.

2. Geetanjali Das and Sandhayarani Biswas, Erosion wear behaviour of coir fiber reinforced epoxy composites filled with Al_2O_3 filler, 2016, Journal of Industrial Textile, doi:10.1177/1528083716652832

Conference Presentations

1. Geetanjali Das and Sandhayarani Biswas, Physical, Mechanical and Water Absorption Behaviour of Coir Fiber Reinforced Epoxy Composites Filled With Al_2O_3 Particulates, 5^{th} National Conference on Processing & Characterization of Materials December 12-13, 2015, NIT Rourkela.

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Vitae

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